

Forest management and regeneration of tree species in the Eastern Amazon

Gustavo Schwartz

Thesis committee

Promotors

Prof. Dr. Ir. G.M.J. Mohren
Professor of Forest Ecology and Forest Management
Wageningen University

Prof. Dr. B.J.M. Arts
Professor of Forest and Nature Conservation Policy
Wageningen University

Co-promotors

Dr. M. Peña-Claros
Assistant professor, Forest Ecology and Forest Management Group
Wageningen University

Dr. J.C.A. Lopes
Researcher, Forest Management and Conservation Group
Embrapa Eastern Amazon, Belém, Brazil

Other members

Prof. Dr. E.C. van Ierland, Wageningen University
Dr. H. ter Steege, Naturalis Biodiversity Center, Leiden
Dr. P. Sist, CIRAD, Montpellier, France
Prof. Dr. R.G.A. Boot, Tropenbos International, Wageningen

This research was conducted under the auspices of the Wit Graduate School for Production Ecology and Resource Conservation (PE&RC)

**Forest management and regeneration of tree species in the
Eastern Amazon**

Gustavo Schwartz

Thesis

submitted in fulfilment of the requirements for degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 18 February 2013
at 4 p.m. in the Aula.

Gustavo Schwartz

Forest management and regeneration of tree species in the Eastern Amazon

Thesis, Wageningen University, Wageningen, NL (2013)

With references, with summaries in English, Dutch, and Portuguese

ISBN: 978-94-6173-466-2

To Simone Ferreira Teichmann,
my wife

Table of Contents

Chapter 1	Forest management and regeneration of tree species in the Eastern Amazon – General introduction	1
Chapter 2	Disturbance level and temporal effects of reduced-impact logging on the regeneration of commercial tree species in the Eastern Amazon (Submitted for publication)	13
Chapter 3	Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon Published in Forest Ecology and Management 274: 116-125	29
Chapter 4	Post-harvesting silvicultural treatments in logging gaps: a comparison between enrichment planting and tending of natural regeneration (Accepted for publication in Forest Ecology and Management)	49
Chapter 5	Profitability of post-harvesting silvicultural treatments applied in logging gaps in the Brazilian Amazon (Submitted for publication)	63
Chapter 6	Synthesis	79
	References	89
	Summary	107
	Samenvatting	111
	Sumário	115
	Acknowledgements	119
	Short biography	123
	List of publications	125
	PE&RC PhD Education Certificate	129
	Funding	131

Chapter 1

Forest management and regeneration of tree species in the Eastern Amazon – General introduction



Mezilaurus lindaviana (Lauraceae)

The Amazon: land use and deforestation

The Amazon encompasses both the largest watershed (the Amazon basin) and the largest continuous tropical forest of the world, corresponding to 60% of all remaining rainforests within the tropics. It covers an area of 6,684 million km² over nine countries (Bolivia, Brazil, Colombia, Ecuador, French Guyana, Guyana, Peru, Suriname, and Venezuela) and plays an essential global role in climate regulation, terrestrial carbon storage, and biogeochemical cycles (Laurance et al., 2002; Mittermeier et al., 2003). The Amazon has a very high biodiversity, comprising 20% of all known animal and plant species of the world, including thousands of tree species (Azevedo-Ramos, 2008; Garda et al., 2010).

Most of the area occupied by the Amazon (60%) is located in Brazil (Fig. 1) and covers more than half of the national territory in nine states (Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins). The region remains relatively isolated from the rest of the country, since historically most of the Brazilian population has inhabited regions close to the coast. Consequently, the Amazon currently holds only 10% of the Brazilian population (20 million people). The colonization of the Amazon has intensified during the last 70 years, due to waves of internal migration from southern and northeastern Brazilian states (Becker, 2005). The migrants are usually poor or landless people attracted by large-scale private or government projects that aim to exploit natural resources, occupy the territory, and integrate the Amazon with the rest of the country. On the other hand, a few migrants with financial capital have arrived from South, Southeast, and Center-West Brazil to profit from timber extraction and cheap land for growing soybean and cattle (Fearnside, 2008).

Heavy investment by the Brazilian Government in the 1960s-1970s in new infrastructure for road transport and energy production in the Amazon resulted in several highways (BR-153, Belém-Brasília; BR-230, Transamazon; BR-364; and BR-319, Porto Velho-Manaus) and two hydropower plants – Balbina in Amazonas state and Tucuruí in Pará state (Kohlhepp, 2000). In addition, the government set up a duty-free trade zone in Manaus (capital of Amazonas) to provide an incentive for colonization and the establishment of industries that would increase jobs and promote technological development. Parallel to these official programs, large private projects of commercial plantations to produce rubber and timber, and the discovery of vast reserves of gold, iron ore, and other valuable minerals in Pará attracted thousands of new migrants (Lins, 1991; Becker, 2005). This massive influx of migrants hugely increased the human pressure and consequently led to intensification of competing claims on natural resources in the Brazilian Amazon.

In the 1950s, due to an increasing population with more access to technology and financial resources for slashing down forests, the region started experiencing deforestation and land degradation at larger scales. Deforestation increased strongly between the late 1970s and late 1980s, but not until 1988 did the National Institute for Space Research (INPE) start making reliable measurements of forest cover in the Brazilian Amazon, based on satellite imagery. The human pressure on the forest resulted in an average deforestation rate of 16,300 km² year⁻¹ in the period of 1988-2011 (INPE, 2012). Although deforestation rates have been falling since 2004 (Hecht, 2011; INPE, 2012), around 20% of the total original forested area in the Brazilian Amazon has been lost.

It has been shown that deforestation rates have been closely related to economic activities, usually increasing when a country's economy is expanding (Lambin et al., 2003; Fearnside, 2005). The increasing world and domestic demand for resources promotes economic activities that are land-demanding, such as cattle ranching, agriculture, and timber production. Such dynamics in the land use may result in uncontrolled logging and deforestation in areas covered by pristine forests (Gerwing, 2002; Monteiro et al., 2004; Fearnside, 2008; Nepstad et al., 2008). The ongoing deforestation and natural resource exploitation is not evenly distributed in the Brazilian Amazon and most of the observed clearing is currently concentrated in the so-called arc of deforestation. The latter represents Brazil's newest land-use frontier in the country: it stretches from the municipality of Paragominas (Pará) to Rio Branco (capital of Acre state) and includes the states of Mato Grosso, Amazonas, and Rondônia (Watrin, 2003; Fearnside, 2005; Rodrigues et al., 2009).

Regardless of the notable environmental losses, many people in Brazil believe that development inevitably implies deforestation. Indeed, in Amazonian municipalities where there has been forest overexploitation and deforestation, socioeconomic standards have improved, as expressed by the Human Development Index (HDI). The standards improved as a result of economic activities related to deforestation, but as the forest resources, they decline towards the pre-deforestation levels. Consequently, deforested municipalities eventually tend to fall back to the same HDI as municipalities that have never experienced deforestation (Rodrigues et al., 2009).

The increasing human pressure accompanied by competing claims on natural resources in the Brazilian Amazon that may lead to decline and degradation brings the need for more sustainable and less destructive land uses that will achieve sustainable development (Homma, 2005; Becker, 2005). One possible option for combining sustainable long-term economic activity with the maintenance of environmental services is the management of

Chapter 1

tropical forests (Silva, 1997; Appanah, 1998; Azevedo-Ramos, 2008; Meyfroidt and Lambin, 2011). The following overview is of silvicultural systems used in the tropics for forest management, their possible application in the Brazilian Amazon, the challenge of ensuring regeneration for future harvests, and possible solutions.

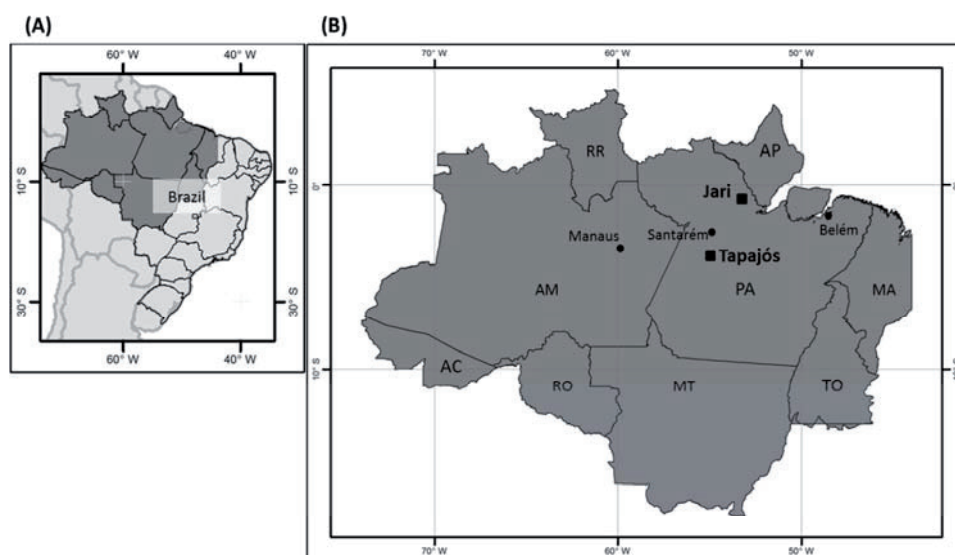


Fig. 1. The Brazilian Amazon (dark grey) within the country borders (A), and (B) showing the states (AC = Acre, AP = Amapá, AM = Amazonas, MA = Maranhão, MT = Mato Grosso, PA = Pará, RO = Rondônia, RR = Roraima, and TO = Tocantins), and the study sites of Tapajós and Jari (black squares).

Management of tropical forests through silvicultural systems

The development of silvicultural systems in tropical forests dates back to the 19th century, when the first attempts were made to introduce management plans for teak (*Tectona grandis*) in Indonesia and India (Lamprecht, 1989; Dawkins and Philip, 1998). Since then, complete silvicultural systems have been developed not only in Asia but also in other tropical forests worldwide. These silvicultural systems have been classified into two main groups: monocyclic and polycyclic systems (see Table 1). The silvicultural systems may also be classified into shelterwoods, efficient for shade-intolerant species, and selection systems, more appropriate for shade-tolerant species (Ashton and Hall, 2011). In the monocyclic systems, timber extraction happens in only one time and the next cutting cycle depends solely

on the regeneration growth, which takes 60 to 100 years to achieve harvestable volume. But in a polycyclic silvicultural system (PSS), cutting cycles are more frequent than the rotation period, since not all harvestable trees are removed at once and the remaining ones ensure that the interval until the next cutting cycle is shorter (Silva, 1997; Table 1).

Table 1

Main characteristics of the monocyclic and polycyclic silvicultural systems developed and applied in tropical forests.

Main characteristics	Shelterwood/ Monocyclic systems	Selection/ Polycyclic systems
Disturbance regime of forest	Strong episodic events	Small and frequent
Type of canopy species	Shade-intolerant	Shade-tolerant
Time for regeneration	Rotation period	Continuous
Silvicultural treatments focus on	Regeneration	Remaining trees
Examples and references	Malayan uniform system (Dawkins and Philip, 1998; D'Oliveira, 2000b), Tropical Shelterwood system (Nyland, 1996; Ashton and Hall, 2011), Seed tree system (Nyland, 1996; Ashton and Hall, 2011), the single cutting systems (Ashton and Hall, 2011)	Malayan selective system (Silva, 1997; Appanah, 1998), Indonesian selective system (Whitmore, 1984; Silva, 1997), Selective logging system – Philippines (Silva, 1989), CELOS (De Graaf, 1986; Jonkers and Hendrison, 2011)

In the Brazilian Amazon, the forestry initiatives were concentrated mainly on adapting silvicultural systems developed elsewhere to the local conditions. The first experimental attempts at forest management in the Brazilian Amazon started in the 1970s (Silva, 1997). The experiments were set up and carried out in Curuá Una and Tapajós, both in Pará state (eastern Amazon), by SUDAM (Superintendence of the Development of the Amazon) and EMBRAPA (the Brazilian Agricultural Research Corporation). They consisted of establishing a PSS adapted from the Malayan Uniform System and the Shelterwood System with selective logging (Matthews, 1989; Dawkins and Philip, 1998; Yared et al., 2000). The outcomes of these attempts plus the results of other forest management experiences begun later in other regions of the Amazon forged the basis for developing the Brazilian PSS. The PSS currently applied in the Brazilian Amazon has a harvesting cycle of 30 years (Fig. 2) and a minimum diameter cutting (MDC) of 45 cm. These values may vary, however, depending on the local forest attributes and purposes of specific management plans (MMA, 2006). The

selected trees are harvested, but the others are left standing; as a result, environmental services are maintained and the forest can be harvested in future cycles (Fig. 2).

YLC-1	YLC-2	YLC-3	YLC-4	YLC-5
YLC-6	YLC-7	YLC-8	YLC-9	YLC-10
YLC-11	YLC-12	YLC-13	YLC-14	YLC-15
YLC-16	YLC-17	YLC-18	YLC-19	YLC-20
YLC-21	YLC-22	YLC-23	YLC-24	YLC-25
YLC-26	YLC-27	YLC-28	YLC-29	YLC-30

Fig. 2. Schematic representation of the yearly logging compartments (YLC). The polycyclic silvicultural system applied in the Brazilian Amazon entails systematically logging the compartments one by one, so that after 30 years (YLC-30) the entire management area has been logged and a new cycle can start in YLC-1.

The PSS currently applied in the Brazilian Amazon has produced remarkable improvements over the past thirty years, thanks to the application of the findings of the long-term experiments and the adaptation of the CELOS Management System in some areas (De Graaf et al., 2003; De Graaf and Eldik, 2011). The CELOS (Centre for Agricultural Research in Suriname) management system, which was also adapted from the Malayan Uniform System into a polycyclic system, has been being developed in Suriname since the 1970s. It is the most known and developed system in the Amazon (Hendriksen and De Graaf, 2011), although it has never been applied at commercial scales. A more recent improvement of the PSS applied in the Brazilian Amazon is the introduction of Reduced-impact logging (RIL) techniques. The main objective of RIL is to improve the efficiency of harvesting operations in PSS, thereby avoiding unnecessary damage to the remaining trees, decreasing chances of forest degradation, and increasing the likelihood of higher yields for the next cutting cycles (Zarin et al., 2007; Putz et al., 2008). RIL complements and refines the harvesting in the PSS applied in Brazil, entailing, among other things, pre-logging activities (e. g. worker training, mapping, tree inventories, road construction, and liana cutting), and techniques of directional felling (Table 2). Brazilian regulations (see MMA, 2006) stipulate that the maximal amount of timber to be harvested is $30 \text{ m}^3 \text{ ha}^{-1}$ in a 30-year cutting cycle with mechanized harvesting, or $10 \text{ m}^3 \text{ ha}^{-1}$ (or 3 trees ha^{-1}) in 10-year long cutting cycles when harvesting low-intensity and

non-mechanized. The MDC may also depend on the species. Some commercial species have a specific MDC, while others have a standard 45 cm MDC. Furthermore, at least 10% of adult trees of the harvested species must be left standing, for seed production.

It has been shown that RIL is more environmentally friendly than the conventional logging (CL) applied most commonly in tropical forests (Pinard and Putz, 1996; Putz et al., 2008; Imai et al., 2009). RIL has low or no impact on various animal communities such as birds (Wunderle et al., 2006) and mammals (Azevedo-Ramos et al., 2006; for bats, see Castro-Arellano et al., 2009; Presley et al., 2009). The genetic diversity of species harvested with RIL techniques is maintained (Cloutier et al., 2007; Silva et al., 2008; Sebbenn et al., 2008; Carneiro et al., 2011) and survival rates of the standing trees do not decrease (Johns et al., 1996; Pereira et al., 2002), which increases the probability of higher yields in future cutting cycles (Zarin et al., 2007; Macpherson et al., 2012). One disadvantage that could be an argument for not adopting RIL is that it costs more to establish than CL (Medjibe and Putz, 2012). However, RIL usually becomes more profitable than CL in the long term, thereby increasing the possibility that a logging company will obtain certification, access carbon markets, and enter markets that demand more quality but are more profitable (Barreto et al., 1998; Boltz et al., 2001; Holmes et al., 2002; Hecht, 2011).

Beyond reduced-impact logging: post-harvesting silvicultural treatments

Despite the improvements and consequent benefits of the PSS with RIL techniques that is applied in the Brazilian Amazon, there are still no examples of any Brazilian Amazonian forest having a second harvesting cycle (30 years) that would enable the efficiency of the given PSS to be assessed. Long-term simulations suggest that in future cutting cycles, the timber yields of species from forests managed under the current practices will be lower (Azevedo, 2006; Van Gardingen et al., 2006; Sist and Ferreira, 2007; Valle et al., 2007; Putz et al., 2008). Possible options to address the problem include adjusting the set of species currently harvested towards the more light-wooded species (Reis et al., 2010), reducing the timber volume harvested, lengthening cutting cycles (Huth and Ditzer, 2001; Hawthorne et al., 2012), and applying silvicultural treatments to future crop trees, to reduce mortality and improve growth (Dauber et al., 2005). Another option is to apply silvicultural treatments for achieving long-term sustainable harvesting in the Amazon (De Graaf et al., 1999). Such treatments are essential when many species are rare, i.e. have less than one individual ha⁻¹ (Schulze et al., 2008).

Table 2

Main characteristics and benefits of reduced-impact logging techniques applied in tropical forests.

Characteristics	Benefits
Pre-logging	
<i>Management plan</i> : identification of harvesting and preservation areas	Decreases impacts of management on wildlife and risks of fire
<i>Forest census</i> : operational planning and 100% trees inventory	Reveals timber volume and allows harvesting activities to be planned better
<i>Harvesting planning</i> : to identify logging compartments, logging decks, skid trails, and planning of directional felling	Decreases damage to the residual forest and helps prevent accidents during felling operations
<i>Liana cutting</i> : applied to trees one year before they are harvested	Decreases damage to the residual forest and helps prevent accidents during felling operations
During logging	
Directional felling	Decreases damage to the residual forest
Planned dragging	Avoids loss of logs and unnecessary soil compaction
Continuously	
Protection against fire	Reduces chances of fire in logged forests
Wildlife conservation	Maintains biodiversity as close as possible to the pre-logging conditions

Problems related to insufficient regeneration of commercial species have been reported in managed tropical forests of the Western Amazon (D'Oliveira, 2000a), Bolivia (Mostacedo and Fredericksen, 1999; Van Rheenen et al., 2004; Park et al., 2005), West Africa (Doucet et al., 2009), and possibly the Eastern Amazon (Falkowski, 2011). Therefore, silvicultural treatments aimed to improve regeneration are necessary (Fredericksen and Pariona, 2002; Schwartz et al., 2012; Soriano et al., 2012). Silvicultural treatments applied in gaps created by logging may be an efficient way of improving the regeneration of commercial species. Examples of such treatments are removing topsoil (Fredericksen and Pariona, 2002; Fredericksen and Putz, 2003), tending the naturally established regeneration by reducing competition from lianas and other trees (Pariona et al., 2003; Park et al., 2005), and enrichment planting (Lopes et al., 2008; Schulze, 2008; Doucet et al., 2009; Keefe et al., 2009).

Tending natural regeneration and enrichment planting might be effective as two complementary post-harvesting silvicultural treatments. If the availability of natural regeneration is sufficient, tending should be preferred. On the other hand, if naturally established regeneration is scarce, enrichment planting in logging gaps may be an acceptable

alternative (D'Oliveira, 2000a; Pariona et al., 2003; Lopes et al., 2008; Schulze, 2008; Keefe et al., 2009; Gomes et al., 2010; D'Oliveira and Ribas, 2011; Chapters 3 and 4). There are, however, few studies on the cost-benefit analysis of silvicultural treatments applied in logging gaps. It has been reported that enrichment planting demands heavy financial investments and may be unprofitable (Lopes et al., 2008; Schulze, 2008; Bais, 2012; Chapter 5).

In view of the above, this thesis aims to contribute to evaluating the effects of harvesting on the natural regeneration of commercial species and to assessing post-harvesting silvicultural treatments that have potential to improve the regeneration of commercial species in the Amazon and other tropical forests.

Study sites

This research was developed in the Eastern Amazon, in two study sites, Tapajós and Jari, both located in the state of Pará, Brazil (Fig. 1, Table 3). The studies in Tapajós were carried out in the Tapajós National Forest, a 600,000-ha federal conservation unit established in 1974 for sustainable using. The various activities permitted in this unit include strictly regulated timber production. The Tapajós National forest is administered by the federal Institute Chico Mendes for Biodiversity Conservation (ICMBio). The study area is located at sign km 83 along the BR-163 highway, 12 km to west in the 546-ha Intensive Study Plot (ISP) established by the Dendrogene project. That project, coordinated by Embrapa Eastern Amazon, had as its main objectives the study of ecological and genetic responses of commercial tree species under RIL (Kanashiro et al., 2002). The forest within the plot had an average density of trees > 10 cm in dbh of 470 stems ha^{-1} (Rice et al., 2004). Based on the pre-logging inventory (including only trees ≥ 45 cm in dbh), there were 212 species with an overall density of 29.5 trees ha^{-1} .

The Jari study site is in the Jari Valley in Almeirim municipality, in the forest management area belonging to the Orsa Florestal S.A. forestry company. The company has been managing natural forests since 2003 in a total area of 545,535 ha, which is FSC-certified. In the same management area the company has *Eucalyptus* plantations for cellulose pulp production (Orsa Florestal, 2012). Orsa Florestal currently sells certified timber to domestic markets and exports to Europe, Asia, and North America. The experiments were carried out in the logging compartment of 2004, under the project “Gap Management” (coordinated by Orsa Florestal and Embrapa Eastern Amazon).

The two study sites have the same biophysical characteristics (Table 3). The forest has been classified as ombrophilous dense, lowland moist forest, or as terra firme forest,

Chapter 1

depending on the classification system used and author (e.g. Eva et al., 2004; IBGE, 2004). This forest type is the most common one in the Eastern Amazon, where most of the forest is managed with PSS and RIL. Another reason for choosing the two study sites was because of the long-term researches carried out there on the PSS and RIL applied in the Brazilian Amazon.

Table 3

Characteristics of the study areas (Tapajós and Jari) in the Eastern Amazon where the experiments were carried out, and information on harvesting.

	Tapajós	Jari
Location	3°02'S – 54°56'W	1°09'S – 52°38'W
Mean altitude (m asl)	175	150
Annual mean temperature	25°C	26°C
Annual rainfall	1,900 mm	2,200 mm
Main type of soil	Yellow latosols	Yellow latosols
Type of forest	Ombrophilous dense	Ombrophilous dense
Cutting cycle (years)	30	30
Species harvested	50	27

Research objectives and questions

The general objective of the research done for this PhD thesis was to study the regeneration ecology of commercial species in order to identify the silvicultural treatments that would help achieve a move towards ecologically and economically sustainable forested land uses. Four specific research questions were addressed:

- 1) How does the regeneration of commercial tree species respond to the different levels of disturbance created by RIL?
- 2) How does the regeneration of commercial tree species respond in the medium term to disturbance caused by RIL?
- 3) Which of the two post-harvesting silvicultural treatments applied in logging gaps is the most suitable: tending the natural regeneration, or enrichment planting followed by tending?
- 4) To what extent are the post-harvesting silvicultural treatments of tending natural regeneration and enrichment planting in logging gaps profitable in the long term?

Thesis outline

This thesis consists of six chapters: this introduction (Chapter 1), four research chapters (Chapters 2 to 5), and a synthesis (Chapter 6).

In Chapter 2, the short-term effect of different levels of disturbance caused by RIL on the density of seedlings of seven commercial tree species in the Tapajós National Forest (Brazil) is assessed. The underlying hypothesis is that RIL will result in an increased density of long-lived pioneers (LLP) and in fewer partially shade-tolerant (PST) species, but will not affect the density or numbers of totally shade-tolerant (TST) species. Furthermore, the LLP should increase in density along a gradient of disturbance levels.

In Chapter 3, the medium-term (six years) responses of seven commercial tree species to RIL are evaluated. The density, growth, recruitment, and mortality rates of seedlings and saplings of these seven species were assessed in the Tapajós National Forest, Brazil. The hypothesis is that densities and growth rates of all species will increase and, over six years, their densities will return to pre-logging levels.

Chapter 4 investigates the ecological responses of seedlings and saplings subjected to two post-harvesting silvicultural treatments in gaps created by RIL in Jari: a) tending of naturally established seedlings and saplings of commercial species and b) enrichment planting with seedlings of commercial species followed by tending. The hypothesis is that, compared with untended individuals, the tended individuals will have lower mortality rates and higher growth rates. The planted individuals will also have lower mortality rates and higher growth rates by comparison with untended plants.

The long-term profitability of the two post-harvesting silvicultural treatments applied in gaps created by RIL in Jari is analyzed in Chapter 5. To do so, the costs and future projected benefits of these silvicultural treatments were compared. The hypothesis is that in the long term, enrichment planting with tending will be a more profitable treatment than tending the natural regeneration.

In Chapter 6, the main outcomes and conclusions of all chapters are summarized and linked with the research objectives and questions presented earlier. In addition, the chapter discusses the silvicultural implications, perspectives and challenges of guaranteeing sufficient regeneration of commercial species in order to achieve environmentally sound and economically viable future cutting cycles in tropical forests.

The approaches underlying the chapters vary. Chapters 2 and 3 describe experiments applied in a forest harvested under RIL techniques in Tapajós since 2002. An experimental approach is also used in Chapter 4, to test two different silvicultural treatments applied since 2006 in logging gaps and compare them with a control. Chapter 5 is based on a cost-benefit analysis followed by a sensitivity analysis.

Chapter 2

Disturbance level and temporal effects of reduced-impact logging on the regeneration of commercial tree species in the Eastern Amazon

Gustavo Schwartz, Marielos Peña-Claros, José C. A. Lopes, Milton Kanashiro, Godefridus M. J. Mohren

(Submitted for publication)



Symphonia globulifera (Clusiaceae)

Abstract

In this study we investigated the effects of reduced impact logging (RIL) on the regeneration of commercial tree species because long-term timber yields depend, among other factors, on the availability of seedlings of commercial tree species in a logged forest. We worked with seven commercial tree species belonging to three functional groups: the long-lived pioneers (LLP) *Bagassa guianensis* and *Jacaranda copaia*; the partially shade tolerant (PST) *Hymenaea courbaril*, *Dipteryx odorata*, and *Carapa guianensis*; and the totally shade tolerant (TST) *Symphonia globulifera* and *Manilkara huberi*. The experiment was carried out in the Tapajós National Forest, eastern Amazon, Brazil. All individuals < 20 cm in diameter were inventoried and measured three times before and twice after logging. The logged area was sampled through 28 transects consisting of 10 x 10 m plots, covering 24.39 ha in total. The average intensity of harvesting was 22 m³ ha⁻¹ or 21% of the original commercial volume. RIL did not have a destructive effect on the harvested forest, 52.5% of the area remained untouched while only 9.2% was highly disturbed by logging operations. All species except *C. guianensis* increased in density after logging. LLP species mainly increased in density in highly disturbed plots, while PST and TST species increased in density in logged plots under low disturbance levels. As logging promoted increases in densities of the studied species, the post-harvesting heterogeneity of micro-environments might be an important component for a sustainable forest management and conservation of commercial species.

Key words: forest ecology; functional groups; Tapajós; timber species.

Introduction

Natural regeneration of commercial tree species is crucial for achieving sustainable forest management in tropical forests (Mostacedo and Fredericksen, 1999; Park et al., 2005). Future harvesting cycles will depend, among other factors, on the availability of seedlings of commercial tree species in a logged forest. In several tropical forests, logging has been reported to have a negative impact on the natural regeneration of commercial species. For example, logging may increase the risk of local extinction of highly valuable and rare species (Grogan et al., 2008; Schulze et al., 2008b; Hawthorne et al., 2012). It has also been claimed that logging largely damages the remaining forest stand, decreasing the potential future economic value of the forest, and increasing the risk of having it converted to other land use options (Foley et al., 2007). Therefore, logging activities and subsequent effects on natural regeneration need to be monitored and evaluated to determine if post-logging interventions are necessary to assure sufficient timber yield for future cutting cycles.

Reduced Impact Logging (RIL) is an environmentally friendly harvesting technique when compared to conventional logging (Pinard and Putz, 1996; Putz et al., 2008; Miller et al., 2011; Edwards et al., 2012). It has been demonstrated that RIL has low or no impact on the diversity of animal communities of several taxa, such as birds (Wunderle et al., 2006; but see Felton et al., 2006), bats (Castro-Arellano et al., 2009), and mammals (Azevedo-Ramos et al., 2006). RIL also appears to have limited effects on the genetic diversity of tree species (Cloutier et al., 2007; Sebbenn et al., 2008). Managed forests under RIL techniques appear to have lower post-harvesting tree mortality (Johns et al., 1996; Pereira et al., 2002), which improves availability of the remaining trees for future cutting cycles (Zarin et al., 2007; Macpherson et al., 2012). Moreover, RIL may be an effective way of reducing carbon losses in tropical forests when compared to other land uses such as cattle-ranching, agriculture, and conventional logging (Imai et al., 2009; Miller et al., 2011). Nevertheless, long-term simulations show that under more intensive harvest cycles (i.e., 30-years cutting cycle and 45 cm in minimum diameter cutting) RIL logged forests are not able to recover their initial basal areas (Sist and Ferreira, 2007; Valle et al., 2007; Sebbenn et al., 2008).

Most of the studies about the effects of RIL focus on trees > 10 cm in diameter (e.g., Bertault and Sist, 1997; Jackson et al., 2002) with few studies focussing on smaller individuals (<10 cm in diameter) or seedlings (e.g., Lopes et al., 2001). Thus, a more detailed knowledge on how RIL affects seedlings and saplings of different functional groups (Poorter et al., 2006), and how these individuals respond to logging disturbance is very much needed (Mostacedo and Fredericksen, 1999; Fredericksen and Mostacedo, 2000). As seedling and

sapling communities are very dynamic and sensitive to changes in environmental conditions (Nicolson et al., 1999; Montgomery and Chazdon, 2002), an assessment including pre-logging conditions is needed to separate the effect of environment from the effect of logging. Furthermore, the effects of RIL have been mostly evaluated by sampling either the entire logged area regardless of the spatial distribution of logging (Peña-Claros et al., 2008a; Imai et al. 2009; Schwartz et al., 2012) or by sampling specific habitats created during logging operations (e.g., Guariguata and Dupuy 1997; Park et al., 2005).

In this study, we used pre- and post-harvesting data to determine the effect of different levels of logging disturbance on (1) the mortality rates of seedlings and saplings and (2) density of the regeneration of commercial tree species. We worked with seven tree commercial species belonging to different functional groups, as functional groups differ in their response to (logging) disturbance. Consequently, we expect that logging disturbance will increase the density of long-lived pioneers (LLP) and partially shade tolerant (PST) seedlings, and that this increase will be proportional to disturbance intensity. On the other hand, we expect that logging disturbances will decrease the density of the totally shade tolerant (TST) seedlings.

Methods

Study area

The experiment was carried out in the Intensive Study Plot (ISP) established by the Dendrogene project (Kanashiro et al., 2002) in the Tapajós National Forest (Pará state, Brazil). The plot is located at sign km 83 along, 12 km to the West, of the BR-163 highway, 03°02'S and 54°56'W. The Tapajós National Forest is a 600,000 ha federal conservation unit in which several activities are allowed, including sustainable timber production. The area has an average altitude of 175 m asl, annual average precipitation of 1,900 mm with a rainy season from December to May, and average temperatures of 24° to 26°C. The predominant soil type is yellow latosol, and the vegetation is classified as dense ombrophilous forest (Veloso et al., 1991). The ISP and surrounding areas had not been subjected to recent human disturbances before this study. Before logging the average tree density was 470 stems ha⁻¹ (for trees > 10 cm in dbh; Rice et al., 2004), and 29.5 trees ha⁻¹ (for trees >45 cm, based on the pre-logging inventory census).

Study species

The seven commercial tree species studied here belong to three ecological guilds: 1) the LLP *Bagassa guianensis* and *Jacaranda copaia*; 2) the PST *Hymenaea courbaril*, *Dipteryx odorata*, and *Carapa guianensis*; 3) and the TST *Symphonia globulifera* and *Manilkara huberi*. Of these, *C. guianensis* and *M. huberi* are the most common ones, while the others are present in low densities (Table 1). These species were the focal species of the Dendrogene project, which main objective was to study the ecological and genetic responses of tree species to reduced-impact logging (RIL). These species were selected because they have a wide distribution in the Amazon, all but *J. copaia* are important commercial timber species, they belong to different functional groups and have different life history characteristics. Hence, these species were considered good representatives of other commercial tree species of the region (Kanashiro et al., 2002).

Table 1

Density of sub-adult (20 cm to < 45 cm in dbh) and adult (≥ 45 cm in dbh) trees of seven commercial species assessed by the Dendrogene project in the Tapajós National Forest, Brazil. The inventory was done before logging in the whole 546-ha Intensive Study Plot. LLP (long-lived pioneer), PST (partially shade tolerant), and TST (totally shade tolerant).

Species	Family	Functional group	Density (# ha ⁻¹)	
			20 – 45 cm (dbh)	≥ 45 cm (dbh)
<i>Bagassa guianensis</i> Aubl.	Moraceae	LLP	0.08	0.15
<i>Jacaranda copaia</i> (Aubl.) D Don	Bignoniaceae	LLP	0.71	0.36
<i>Hymenaea courbaril</i> L.	Fabaceae	PST	0.14	0.29
<i>Dipteryx odorata</i> (Aubl.) Willd.	Fabaceae	PST	0.03	0.12
<i>Carapa guianensis</i> Aubl.	Meliaceae	PST	3.97	1.39
<i>Symphonia globulifera</i> L. f.	Clusiaceae	TST	0.39	0.08
<i>Manilkara huberi</i> (Ducke) A. Chev.	Sapotaceae	TST	1.04	1.53

Experimental design and measurements

The ISP has an area of 546 ha that was split into eight blocks ranging in size from 40 – 100 ha and separated by 200 – 1,200 m. Blocks were inventoried for commercial trees ≥ 45 cm by the forestry company before logging. In seven blocks we established 3-5 transects to evaluate the regeneration of the seven target species, making a total of 28 transects. The last block (with 46 ha, block #8) was never logged, and was used as the control plot in other studies (e.g. Schwartz et al., 2012). This block was not included in this study.

Logging was carried out in the ISP plot (in seven out of eight blocks) from August to December 2003. Logging was done by the Treviso/Maflops forestry company according to RIL techniques and the Brazilian environmental restrictions concerning the management of old-growth forests. The average intensity of logging was $22 \text{ m}^3 \text{ ha}^{-1}$, representing 21% of the original commercial volume ($105 \text{ m}^3 \text{ ha}^{-1}$) of timber, in trees $\geq 45 \text{ cm}$ in dbh. Such logging intensity corresponded to $3.5 \text{ trees ha}^{-1}$ (Miller et al., 2007). Trees of 46 species were harvested, including the seven focal species of this study.

Transects were 10 m wide and 400-1,000 m long depending on the block shape, and were subdivided in $10 \times 10 \text{ m}$ plots, making a total of 2,439 plots with 24.39 ha sampled in a total area of 500 ha. In each $10 \times 10 \text{ m}$ plot we surveyed for individuals of the seven focal species. Identified plants were measured in height for seedlings and saplings (plants $< 300 \text{ cm}$ in height) or dbh for juvenile trees (individuals $\geq 300 \text{ cm}$ in height and $< 20 \text{ cm}$ in dbh). All plants were mapped and tagged. We carried out three pre-logging (September 2002, February 2003, and June 2003) and two post-logging surveys (in January 2004 and in September 2004). We searched for recently germinated and dead individuals, and we measured height or dbh of all plants in three evaluations: September 2002 (plot establishment), June 2003, and September 2004. In the pre-logging assessment carried out in February 2003 only mortality was evaluated. In the post-logging assessment taken in January 2004 mortality directly due to logging operations and natural mortality were quantified.

Forest structure was assessed by describing the forest-phase of each individual plot at each assessment. For this study we only considered two stages, according to Whitmore (1982) and Lopes (1993): gap-phase when the plot has a canopy openness $\geq 50\%$, and non-gap-phase when the plot has a canopy openness $< 50\%$. Canopy openness was visually evaluated by two persons standing in the middle of each plot at each measurement. In January 2004 (immediately after logging) plots were assessed for logging impact, defined as any damage caused within the $10 \times 10 \text{ m}$ plots by logged trees located in or outside the plots, and by skid trails. Based on this information, and from the data on forest structure collected during the five evaluations, it was possible to categorize each individual plot into a gradient of disturbance level (low to high disturbance), taking into account whether the disturbance was natural or due to logging. The categories and the number of plots (and percentage of total) per category were: 1) unlogged plots that remained as non-gap-phase over all five assessments, hereafter referred as “unlogged with low natural disturbance”; 2) unlogged plots that had at least one gap-phase in all assessments, hereafter “unlogged with high natural disturbance”; 3) logged plots that remained as non-gap-phase over pre- and post-logging

measurements, hereafter “logged with low logging disturbances”; 4) logged plots under non-gap-phase before logging that shifted to gap-phase in the last measurement because of logging, hereafter “logged with high logging disturbance”; and 5) logged plots that were at least once under gap-phase before logging, hereafter “logged with high natural and logging disturbance”.

Data analysis

Densities were calculated per species per plot for plants < 300 cm in height using data from three assessments: September 2002, June 2003, and September 2004. For assessing the effect of time and the different disturbance levels on densities of each species through time, we performed a mixed model with repeated measures ANOVA (Field, 2005), having disturbance level as the between subject factor, time as the within subject factor, transect as the random factor, and $\ln(\text{density})$ as the dependent variable.

To determine the underlying processes regulating the changes in density through time, recruitment and mortality rates were calculated according to standard methods applied in tropical forests (Sheil et al., 1995; Condit et al., 1999; Losos and Lao, 2004). Recruitment and mortality rates were calculated per species in the whole experiment rather than per plot because of the small sample size per species per plot. Both mortality and recruitment rates were calculated taking into account all individuals counted in each of the evaluations done (3 for recruitment, 5 for mortality). To calculate the recruitment rate we used the following formula:

$$r = (\ln n_t - \ln S_t)/t$$

and for mortality rate:

$$m = 1 - (n_t/n_0)^{1/t}$$

where n_t is the population size at time t , S_t the number of survivors from the initial population size, and n_0 is the initial population size.

Damage and mortality of the seven studied species were assessed four times (February 2003, June 2003, January 2004, and September 2004) during the evaluation period. Annualized mortality rates were calculated for each of four periods for individuals < 300 cm and ≥ 300 cm in height, using the abovementioned formula. As the measurement done in January 2004 took place few days after logging operations had finished in the ISP, it was possible to determine the cause (natural or logging) of death of each individual assessed. Finally, we calculated the basal area of individuals ≥ 300 cm in height and up to 20 cm in dbh, which was compared before and after logging for assessing damage caused by RIL. This was

tested through a mixed model with repeated measures ANOVA, with time as within factor, transect as a random factor, and $\ln(\text{basal area})$ as the dependent variable (all species pooled). $\ln(x+1)$ transformation was used to increase variance homogeneity and normality of the variable density. Statistical analyses were performed with the SPSS software, version 19.0.

Results

Mortality and damage caused by logging

RIL directly affected 47.5% of all sampled plots, being 5.9% severely affected by logging, and 3.3% by both logging and natural disturbances. At the first evaluation after logging (January 2004) we found that 2,152 individuals < 300 cm in height were dead (representing 30.2% of all monitored individuals), being 902 (41.9%) of them dead directly due to logging. In the case of individuals ≥ 300 cm in height, we found 37 dead individuals (0.5% of all monitored individuals), of which 73% because of logging. The additional mortality due to logging substantially increased the mortality rate of both size classes. By September 2004 (nine months after logging) mortality rate had not returned to the initial values yet (Fig. 1). The mortality of damaged individuals (i.e., broken individuals) increased also after logging (Fig. 1). Finally, the total basal area of individuals ≥ 300 cm in height up to < 20 cm in diameter did not vary through time, even after logging (Repeated Measures ANOVA, $F_{4,4877} = 0.1$, $p = 0.991$).

Density of individuals < 300 cm in height

All species varied in density through time (Fig. 2, Table 2: see column time). Densities of all species except *J. copaia* had no pre-logging variation (Fig. 2, see period September 2002 to June 2003). After logging, all investigated species increased in density, except *C. guianensis*, which slightly declined (Fig. 2, see period June 2003 to September 2004). *B. guianensis* presented a large increase from low densities (0.16 and 0.20 individuals ha^{-1}) in the two first measurements to 18.94 individuals ha^{-1} in the post-logging survey. Other species such as *J. copaia*, *H. courbaril*, and *D. odorata* increased more than fivefold in their densities after logging.

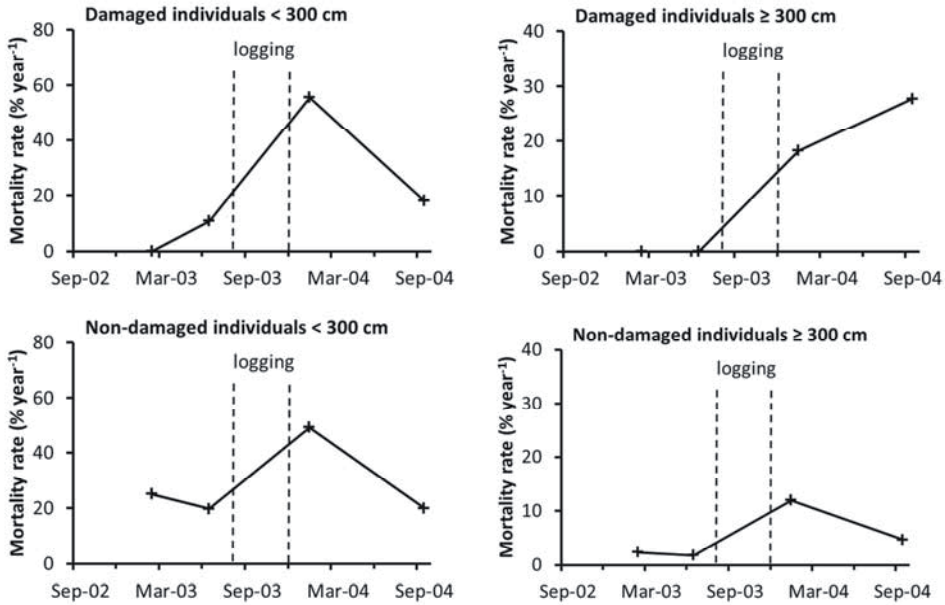


Fig. 1. The overall mortality rates of damaged and non-damaged individuals < 300 cm in height and ≥ 300 cm in height to < 20 cm in dbh of the study species before and after logging, in the Tapajós National Forest, Brazil. Note that the scale of y-axis varies.

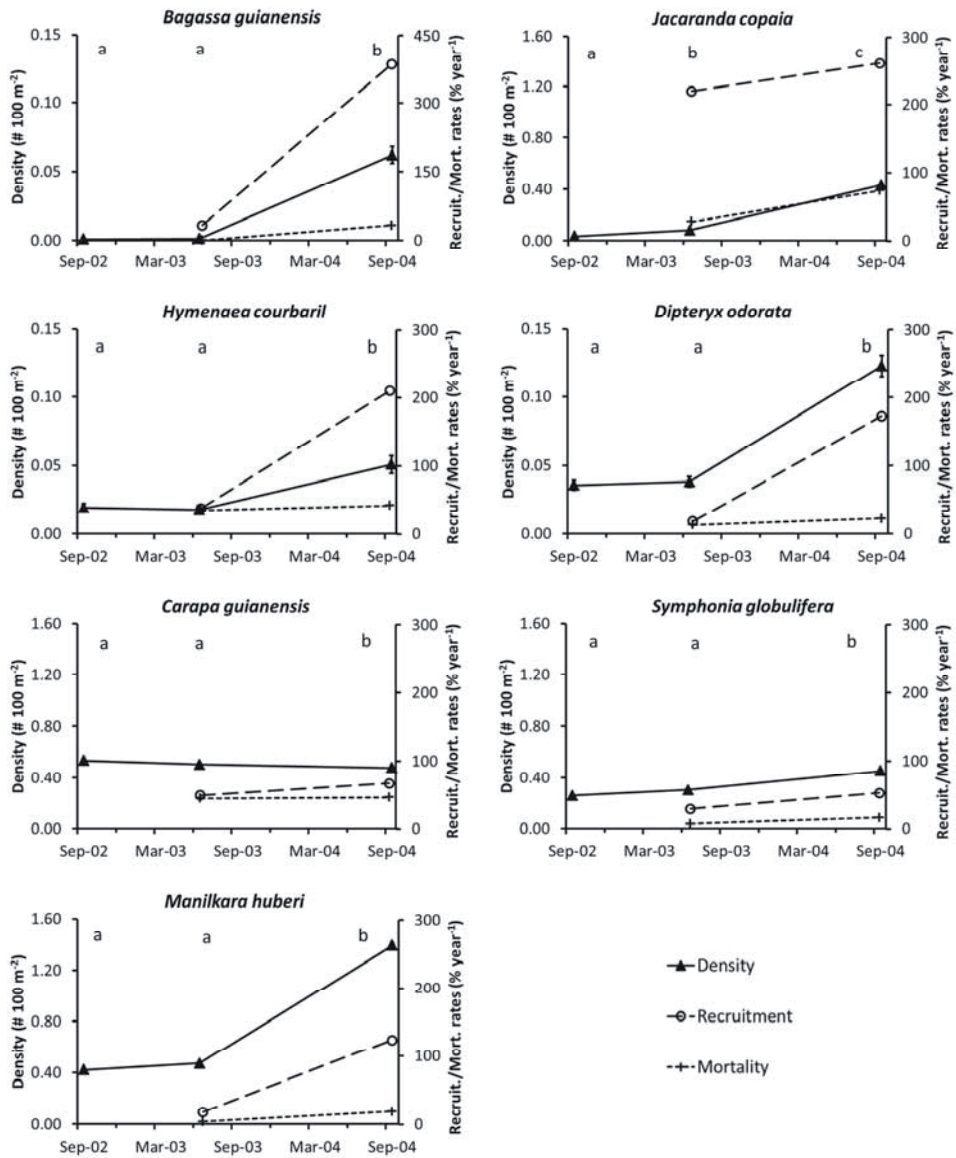


Fig. 2. Density, recruitment, and mortality rate of individuals < 300 cm in height belonging to seven commercial tree species in the Tapajós National Forest. Data are average \pm 1.0 SE. The scale of y-axis varies among species. Letters indicate statistical differences through time over treatment ($p < 0.05$ – pairwise comparisons).

Table 2

Density under five disturbance levels (including pre- and post-logging censuses) of commercial tree species in the Tapajós National Forest, Brazil. Both data sets were analysed with Repeated Measures ANOVA with transects as a random factor. F values and p values are given (ns: non-significant. *: $0.01 \leq p < 0.05$. **: $0.001 \leq p < 0.01$. ***: $p < 0.001$).

Species	Density per disturbance level		
	Time	Disturbance level	Time x Disturbance level
<i>B. guianensis</i>	35.6; $p < 0.001$ ***	40.0; $p < 0.001$ ***	20.2; $p < 0.001$ ***
<i>J. copaia</i>	214.9; $p < 0.001$ ***	135.2; $p < 0.001$ ***	90.2; $p < 0.001$ ***
<i>H. courbaril</i>	3.2; $p = 0.042$ *	2.8; $p = 0.025$ *	0.7; $p = 0.714$ ns
<i>D. odorata</i>	9.3; $p < 0.001$ ***	2.2; $p = 0.062$ ns	1.0; $p = 0.401$ ns
<i>C. guianensis</i>	3.2; $p = 0.039$ *	21.7; $p < 0.001$ ***	1.8; $p = 0.068$ ns
<i>S. globulifera</i>	5.5; $p = 0.004$ **	12.0; $p < 0.001$ ***	1.9; $p = 0.059$ ns
<i>M. huberi</i>	76.1; $p < 0.001$ ***	16.1; $p < 0.001$ ***	4.6; $p < 0.001$ ***

Spatial effects of logging

Densities of all species varied over time and the disturbance level had a significant effect on the density of all species, except *D. odorata* (Table 2). Logging strongly increased densities of LLP. *B. guianensis* increased from zero to 0.94 individuals plot⁻¹ in plots with high logging disturbance. *J. copaia* density varied through time with the level of disturbance. Its density only increased through time in logged plots, especially in those ones under high logging disturbance (Table 2, Fig. 3).

The PST species unveiled contrasting responses to disturbance. Densities of *H. courbaril* only slightly increased through time, while in the case of *D. odorata* the increase in density did not vary due to disturbance level (Table 2, Fig. 3). *C. guianensis* declined in density under high natural or logging disturbances, and tended to maintain the same number of individuals in unlogged plots (Fig. 3). Finally, in the case of the two TST species (Table 2, Fig. 3) *S. globulifera* increased in density in all disturbance levels, except in plots under high logging disturbance. The density of *M. huberi* increased in all categories through time, being the increase larger in plots undergoing logging disturbance (Fig. 3).

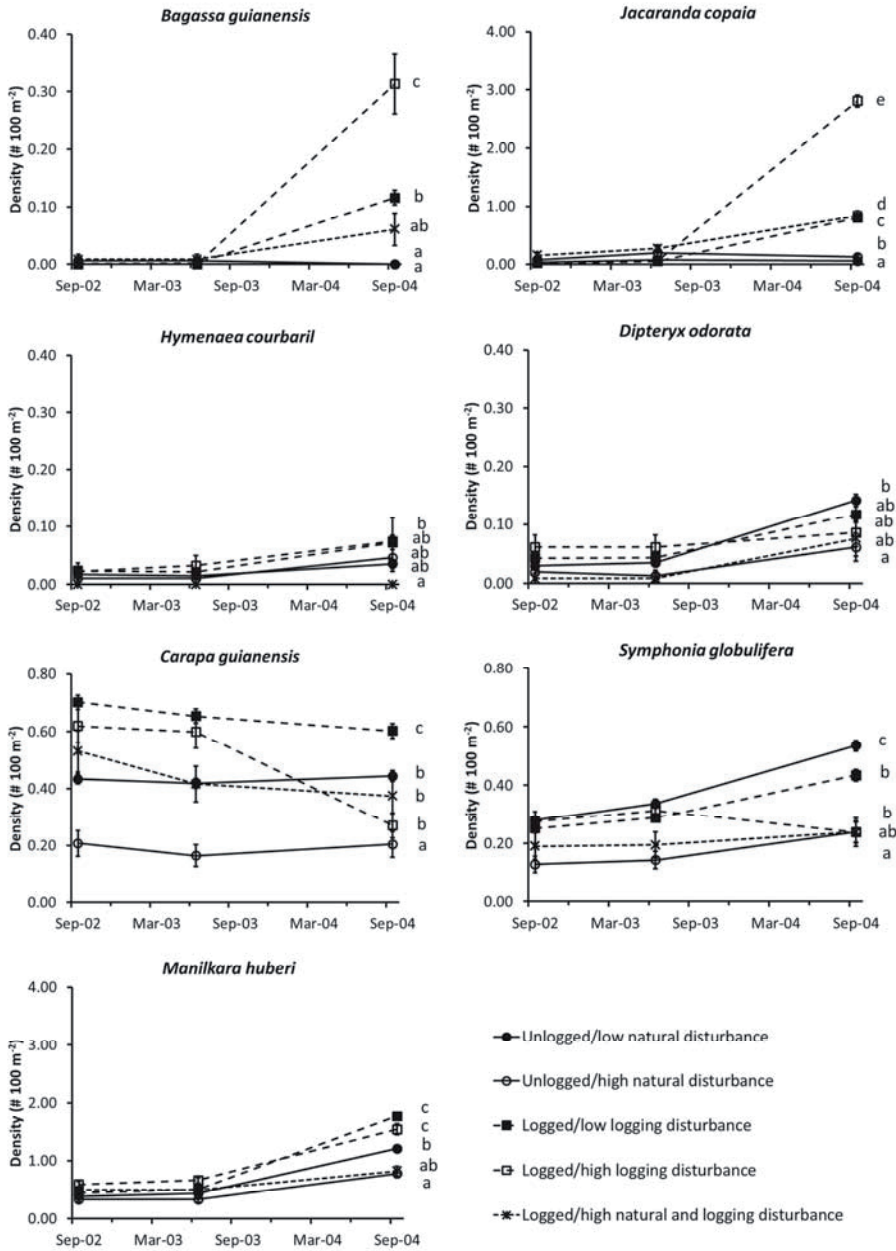


Fig. 3. Density of individuals (< 300 cm in height) belonging to seven commercial species in five levels of disturbance in the Tapajós National Forest, Brazil. The disturbance differs in its origin (natural and logging) and intensity (low vs. high). The scale of y-axis varies among species. Letters indicate overall effect of disturbance level ($p < 0.05$ – pairwise comparisons).

Logged plots subjected to higher disturbance levels showed higher recruitment and mortality rates than plots with low disturbance levels. Such differences did not exist before logging when plots showed similar recruitment and mortality rates (Fig. 4).

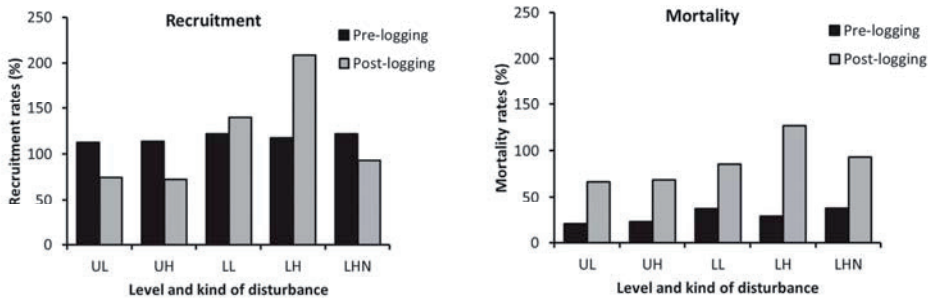


Fig. 4. Pre- and post-logging recruitment and mortality rate in plots under different disturbance levels. Plots were classified according to disturbance level after logging, and then used in the pre-logging data to compare recruitment and mortality rates in the same plots. UL = unlogged plots with low natural disturbance, UH = unlogged plots with high natural disturbance, LL = logged plots with low logging disturbance, LH = logged plots with high logging disturbance, and LHN = logged plots with high natural and logging disturbance.

Discussion

Low damage to the forest

Reduced-impact logging (RIL) had an impact on 47.5% of all sampled plots, with only a small proportion of the plots being severely damaged by logging (5.9%). These results indicate that logging impact is not homogeneously distributed in a logging compartment, and that it results in the creation of a diversity of micro-environments, ranging from undisturbed closed forests to logging gaps. The low destructive interference of logging corroborates other studies, which also show low damages caused by RIL (Bertault and Sist, 1997). This is due to the strict application of RIL methods and to the relatively low timber volume harvested ($22 \text{ m}^3 \text{ ha}^{-1}$) in Tapajós, which corresponds to one fifth of the timber volume before logging. The harvested volume was lower than $30 - 50 \text{ m}^3 \text{ ha}^{-1}$ in another eastern Amazon area (Uhl and Vieira, 1989), $35 \text{ m}^3 \text{ ha}^{-1}$ in Cameroon (Foahom and Schmidt, 2011), and $50 - 250 \text{ m}^3 \text{ ha}^{-1}$ in Indonesia (Sist and Nguyen-Thé, 2002) but higher than in other areas of the Tapajós National Forest (Sablayrolles et al., 2011) and sites in Bolivia (Jackson et al., 2002; Dauber et al., 2005). Volumes between 20 and $30 \text{ m}^3 \text{ ha}^{-1}$ in polycyclic systems generally lead to little disturbance of the ecosystem (Hendrison and De Graaf, 2011).

Mortality rates increase after logging

The overall mortality rates observed in both size classes only increased immediately after logging (Fig. 1), showing a direct influence of logging on the survival of seedlings, saplings, and juvenile trees. Such impact was still present nine months after logging had finished, as mortality rates of damaged plants remained high or even increased for individuals ≥ 300 cm in height. Larger plants suffered less mortality due to logging operations (Fig. 2) than smaller plants, but they were more exposed to injury (the percentage of damaged individuals < 300 cm in height was 4.0% while for plants ≥ 300 cm and up to 10 cm in dbh was 8.6%). The logging effect on larger plants was, however, limited as the total basal area of juvenile trees did not significantly change over logging. Despite the lack of data, we expect a higher percentage of injury on taller individuals (≥ 20 cm in dbh) in the study area as showed by Bertault and Sist (1997) in East Kalimantan (Indonesia). These authors describe a continuous increase in damage combined with a decrease in mortality due to RIL on individuals from 10 cm to 50 cm in dbh. The same pattern is described by Whitman et al. (1997) for Central America.

After logging, densities increase

Our analysis showed no change in densities under pre-logging conditions, except for *J. copaia* (Fig. 2), that may be reflecting a year with higher fruit production. After logging all species, except *C. guianensis*, increased in density (Fig. 2, see period June 2003 to September 2004). The underlying factor behind higher post-harvesting densities (from 271 to 724 individuals ha^{-1}) was an increase in recruitment rates, especially noted in *H. courbaril*, *D. odorata*, and *M. huberi* (Fig. 2). Similarly, mortality rates also increased, being up to four times higher in the case of *J. copaia* and *M. huberi*. This increase was, however, lower than the increase in recruitment rates for six out of the seven studied species (Fig. 2), resulting in a net increase in density. Such variation in density is very much likely related to the change in abiotic conditions in the managed forest. Amongst changes, higher light levels probably lead to an increase in recruitment (see Blate, 2005). The changes in recruitment and mortality rates observed may probably last only for a short period of time as the forest recovers from logging. Schwartz et al. (2012), in the same area, concluded that augmented post-logging densities and growth rates of seedlings and saplings tend to return to pre-logging values within six years.

As expected both LLP and (most) of the PST species had a strong positive response to logging disturbance. This result is consistent with other studies (Lopes et al., 2001, Peña-Claros et al., 2008a; Swaine and Agyeman, 2008). Contrary to our expectations we also found that TST species increased in density (Fig. 2, see *M. huberi*, and *S. globulifera*), mostly in areas subjected to low logging disturbance levels (Fig. 3). In the case of *M. huberi* the increase was substantial, and it might have been related to a mass fructification in the area in August to September 2003 (Schwartz et al., 2012), considering that irregular fruiting cycles are often seen in Amazonian species (Maués, 2006). Only one PST species, *C. guianensis*, presented a small but constant decline in density over all measurements. This species presents a highly aggregated distribution (Klimas et al., 2007; Tonini et al., 2009) in shaded environments. Therefore, its decline in density suggests that the species may be more sensitive to canopy openings, mainly related to water stress during the dry season (June – November). Furthermore, seed predation may have had some influence on densities of *C. guianensis*, because the species has a clumped distribution, offering good foraging sites (Jansen and Zuidema, 2001).

Disturbance increases densities

The results found in this study show that RIL created a gradient of disturbance in the Tapajós National Forest. Almost half of the managed area remained untouched, being subjected to only low natural disturbance. The approximately 10% of the plots exposed to a high disturbance level due to logging, showed the largest increases in density, especially in the case of the LLP species, as we had predicted (Fig. 3). At the same time RIL allowed for untouched plots to remain, with densities of the studied species remaining basically the same as in the pre-logging conditions (Fig. 3). The fact that all shade tolerant species increase in density in plots with intermediate disturbance levels (i.e., logged plots with low disturbance) suggests that the RIL may have a beneficial effect for a variety of species, not only for light demanding ones. This effect of RIL probably also increased the densities of non-commercial species, such as non-commercial pioneers and lianas (Fredericksen and Putz 2003; Sist and Brown, 2004).

RIL does not seem to negatively impact the regeneration of the studied species because no large reduction in seedling and sapling densities was observed (Fig. 3). This is in accordance with other studies elsewhere (Gómez, 2011, Swaine and Agyeman, 2008; Edwards et al., 2012). Although *C. guianensis* showed a small reduction in seedling density, the species does not seem to be threatened by RIL because recruitment rates did not change

after logging. On the contrary, our results show that RIL created conditions for increasing recruitment rates, which was reflected in larger seedling densities. These positive effects of RIL are the result of a combination of factors: the strict application of the RIL guidelines (Zarin et al., 2007) and probably a low harvested volume of $22 \text{ m}^3 \text{ ha}^{-1}$ (21% of the original inventoried commercial volume). This low disturbance resulted in a mosaic of micro-environments where chances for the establishment of the natural regeneration were maintained and in some cases even improved.

Conclusions

Reduced-impact logging (RIL) applied in combination with low harvesting volumes does not have negative effects on the densities of seedlings, saplings and poles of tree species representing a variety of functional groups in the Tapajós National Forest. RIL triggered a major recruitment event, leading to increased seedling densities. At the same time logging disturbances created a mosaic of micro-environments, ranging from a few highly disturbed areas to large areas subjected to low natural and logging disturbance levels. This diversity of micro-environments is a pre-requisite for sustainable forest management as tree species have different regeneration requirements.

Chapter 3

Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon

**Gustavo Schwartz, Marielos Peña-Claros, José C. A. Lopes, Godefridus M. J. Mohren,
Milton Kanashiro**

(Published in Forest Ecology and Management 274: 116-125)



Tapajós National Forest (Km 82) – Brazil

Abstract

Reduced-impact logging (RIL) is a set of techniques aimed to maintain forest structure and functions of the harvested forest as similar as possible to pre-logging status, while reducing adverse impacts from logging activity on the remaining forest. We analysed the mid-term effects of RIL on the regeneration of the long-lived pioneers (LLP) *Bagassa guianensis* and *Jacaranda copaia*; the partially shade tolerant (PST) *Hymenaea courbaril*, *Dipteryx odorata* and *Carapa guianensis*; and, the totally shade tolerant species (TST) *Symphonia globulifera* and *Manilkara huberi*. This study was carried out in an intensive studied plot in the 600,000-ha Tapajós National Forest, Eastern Amazon – Brazil (03°02'S and 54°56'W). Three transects split in 10x10 m plots, adding up to 2.37 ha were sampled in an area where RIL was applied, and compared with a same size sampling in an unlogged area. The regeneration of individuals ≤ 20 cm in dbh was inventoried and measured before logging in 2003 and three times after logging (2004, 2006, and 2009). RIL modified the forest structure creating more gap-phase plots, with the consequences of such disturbance still remaining after 6 years. Densities of *B. guianensis*, *J. copaia*, and *S. globulifera* increased, while *C. guianensis* diminished. The positive effect on the density of LLP species was, however, ephemeral and disappeared 2 years after logging. RIL had a positive effect on the height growth rate of *S. globulifera* and on the dbh growth rate of *C. guianensis*. Plants growing in the gap-phase plots had higher height growth rates (ANOVA, $F_{2,2980} = 33.3$, $p < 0.001$) than plants growing in other phases, but the same difference was not observed for dbh growth rates (ANOVA, $F_{1,364} = 0.9$, $p = 0.33$). Crown position had positive effects on height and dbh growth rates: the higher the crown position, the faster the plant grows in height (ANOVA, $F_{3,2979} = 148.4$, $p < 0.001$) and dbh (ANOVA, $F_{3,362} = 26.1$, $p < 0.001$). The application of RIL following the Brazilian regulations, may be considered a silvicultural technique for increasing density and growth rates of commercial species, but additional silvicultural interventions, as liberation for example, might be required for maintaining the ecological outcomes of RIL in the long run.

Key words: Silviculture; forest ecology; functional groups; Tapajós

Introduction

Reduced-impact logging (RIL) is a set of techniques aimed to keep the structure and functions of the stand forest as similar as possible to pre-logging conditions, while reducing adverse impacts from logging activity on the remaining forest (Zarin et al., 2007). It has been shown that RIL may be more profitable than conventional selective logging (Verissimo et al., 1992). In ecological terms, RIL results in less damage to the forest stand when compared to conventional selective logging (Pereira et al., 2002), has none or minimum negative effects on mammals (Azevedo-Ramos et al., 2006; Presley et al., 2009), or on the gene pool of the harvested tree populations (Sebbenn et al., 2008). Consequently, RIL is seen as an important tool for conserving biodiversity in areas under forest management. RIL is also considered a much better logging practice in the Brazilian Amazon (Carvalho et al., 2008; Schulze et al., 2010), and is being heavily promoted by certified forestry companies.

An adequate level of commercial species regeneration is crucial for achieving sustainable yields in future harvesting cycles (Mostacedo and Fredericksen, 1999; Park et al., 2005). In tropical forests, regeneration may depend on natural disturbances (Fredericksen and Putz 2003). Disturbances caused by logging may affect regeneration of valuable tree species in different ways (Gómez, 2011; Herrero-Jáuregui et al., 2011). Canopy opening increases the density and growth rates of both light-demanding (Nabe-Nielsen et al., 2007) as well as shade-tolerant species (Toledo-Aceves et al., 2009). On the other hand, soil compaction caused by heavy machinery may have a negative effect due to impediment of water infiltration and root penetration of seedlings and saplings (Van Rheen en et al., 2004; Mello-Ivo and Ross, 2006). Furthermore, large canopy openings can promote invasion of non-commercial tree species and lianas, thus increasing competition with seedlings and saplings of valuable species (Fredericksen and Mostacedo, 2000).

Problems achieving regeneration of commercial species after logging, especially of light-demanding species, have been reported in Bolivian forests (Mostacedo and Fredericksen, 1999; Park et al., 2005), which demand specific silvicultural treatments (Jackson et al., 2002). Even if recruitment rates are high, additional post-logging silvicultural interventions may be necessary for improvement of recruitment and increase of survival and growth rates of seedlings and saplings of commercial species (Pariona et al., 2003). It has been shown that RIL has positive effects on the regeneration of commercial tree species in Malaysian forests (Pakhriazad et al., 2010). However, there is a lack of knowledge about the effects of RIL on density and growth rates of seedlings and saplings of harvested species in the Eastern Amazon. Possible consequences of RIL for regeneration in the region are

insufficiently understood, and it is unclear whether future yields in management systems using RIL are safeguarded.

This study was carried out in an area, which was logged using RIL techniques in the Tapajós National Forest, Eastern Amazon – Brazil, and the performance of seven commercial tree species was evaluated from 2003 to 2009. Our objectives were: (1) to assess changes in forest structure through time, resulting from RIL; (2) to evaluate the effect of RIL on the density and growth rates of the main tree species in the forest; and (3) to recommend possible silvicultural treatments to secure sufficient regeneration for following cutting cycles in managed eastern Amazon forests.

Materials and methods

Study area

The experiment was carried out in the 546-ha Intensive Study Plot (ISP) established by the Dendrogene project (Kanashiro et al., 2002) in the Tapajós National Forest (Pará state, Brazil), which aimed to investigate the ecological and genetic responses of seven commercial tree species to RIL. The study plot is located at km sign 83 along the BR-163 highway, 12 km to the west, inside the reserve (03°02'S, 54°56'W). The Tapajós National Forest is a 600,000 ha federal conservation area for sustainable timber production. The area has a mean altitude of 175 m, annual average precipitation of 1900 mm, with a rainy season from December to May, and average temperatures between 24° to 26°C. Soils are classified as yellow latosols. The vegetation is classified as ombrophilous dense forest (Veloso et al., 1991).

Study species

The seven species chosen represent different ecological guilds and have high commercial timber value, with the exception of *Jacaranda copaia* (Table 1). These species represent 14.4% of the total volume of trees ≥ 45 cm in diameter inventoried in the ISP, with *Carapa guianensis* and *Manilkara huberi* having the highest volume and population density among the studied species (Dendrogene project, unpublished data).

Experimental design

The 546-ha ISP was split into eight blocks ranging in size from 40 – 100 ha. They were commercially inventoried for trees ≥ 45 cm in diameter at 1.3 m aboveground (dbh) by the Treviso Maflops forestry company, which was responsible for the logging operations in

the ISP. Additionally, in September 2002 all individuals of the seven target species were inventoried in 3-5 transects established in seven of the eight blocks. Transects were 10 m wide and 400-1000 m long depending on the block shape, totalling 24.39 ha of sampled area. Individuals of the focal species were measured, mapped, and tagged. In July 2003 the last block (block 8) was established as a control. All blocks except block 8 were logged using RIL techniques from August to December 2003. The inventoried timber for trees ≥ 45 cm in diameter was $105 \text{ m}^3\text{ha}^{-1}$, and the volume harvested was $22 \text{ m}^3\text{ha}^{-1}$ (21% of the original volume). Trees of 46 species were logged, among which were the seven focal species of this study.

Table 1

List of commercial tree species assessed by the Dendrogene project in the Tapajós National Forest, Brazil. The ecological groups, main uses of the species, volume (% of the total inventoried volume) and density (individuals/ha) of stems $\geq 45\text{cm}$ in dbh are provided. Total volume and density data are based on a commercial inventory carried out in the 546-ha Intensive Study plot of the Dendrogene project (unpublished data). LLP = Long-Lived Pioneer, PST = Partially Shade Tolerant, and TST = Totally Shade Tolerant.

Species	Family	Ecological Group	Product	% total volume	Density (trees/ha)
<i>Bagassa guianensis</i>	Moraceae	LLP	Timber	0.9	0.15
<i>Jacaranda copaia</i>	Bignoniaceae	LLP	Timber	0.9	0.36
<i>Hymenaea courbaril</i>	Fabaceae	PST	Timber	2.7	0.29
<i>Dipteryx odorata</i>	Fabaceae	PST	Timber	0.7	0.12
<i>Carapa guianensis</i>	Meliaceae	PST	Timber/Oil	2.8	1.39
<i>Symphonia globulifera</i>	Clusiaceae	TST	Timber	0.3	0.08
<i>Manilkara huberi</i>	Sapotaceae	TST	Timber/Gum	6.1	1.53

To assess the ecological mid- and long-term responses of the regeneration to RIL only two blocks (the control and a logged one, separated by a distance of 1,200 m) continued to be re-measured over time. The reduction of monitored blocks in further measurements was due to funding constrains. Given that in the control block it was possible to continue monitoring three transects with lengths of 980 m, 820 m, and 570 m (total = 2370 m), it was decided to use the same sampling effort for the logged block. These transects were monitored in October 2004, November 2006, and December 2009. To facilitate this, monitoring transects were split into 237 10x10 m (100 m^2) plots.

For each plot, we assessed changes in forest structure through time by describing the forest-phase of each plot at each measurement. Three forest-phases were considered and

adapted from Whitmore (1982): gap-phase when the canopy openness is $\geq 50\%$ in the plot; building-phase when $< 50\%$ of canopy openness without any tree ≥ 45 cm in dbh, and mature-phase when $< 50\%$ of canopy openness with, at least, one tree ≥ 45 cm in diameter inside the plot. The canopy openness was visually evaluated by two persons at the same time. Additionally, in each plot we searched for individuals of all seven species, ranging in size from recently germinated seedlings to trees with < 20 cm dbh.

All individuals of the seven species found in the plots were measured in height (for plants < 300 cm in height) or dbh (for individuals ≥ 300 cm in height and < 20 cm in dbh) through time. New individuals (i.e., recently germinated one) of the seven species were searched during each re-measurement. These new individuals were also mapped, tagged, and measured through time. Finally, the light incidence on each individual was estimated using the crown position index (Clark and Clark, 1992): 1.5 (low indirect light incidence on the plant), 2.0 (indirect light), 2.5 (lateral direct light), and 3.0 (overhead light incidence). Dead and recruited individuals were also registered, measured, and mapped in each measurement.

Data analysis

For assessing the effects of RIL on forest structure, we compared the frequency distribution of forest-phases in logged and unlogged forests using the Chi-square test. This test was done per year to assess changes through time. Densities were calculated per species per plot separately for those plants less than 300 cm in height and for those over 300 cm in height. To determine the effect of logging on density a Repeated Measured ANOVA was used, with time and logging treatment as factors and density as the dependent variable (Field, 2005).

Recruitment and mortality rates were calculated according to standard methods applied in other tropical forests (Condit et al., 1999; Losos and Lao, 2004). For recruitment rate, the following formula was used:

$$r = (\ln n_t - \ln S_t) / t$$

and for mortality rate:

$$m = (\ln n_0 - \ln S_t) / t$$

where n_t is the population size at the end of the experiment (time t), S_t is the number of survivors at time t , and n_0 is the initial population size.

Growth rate was calculated at the individual level for plants that remained alive during all measurements. It was calculated in two ways depending on the time interval considered.

For growth rates between two measurements the difference in height between the second and first measurement was divided by the time elapsed (in years). For overall growth rates individual height or dbh measurements were regressed over time, using all available measurements. The slope of the linear regression was then multiplied by 365 days to obtain the growth rate per year. Plants with negative height growth rates were kept in the analyses. Individuals that started being measured in height and became ≥ 300 cm in height had their dbh measured in later measurements (for four species); consequently, to be able to calculate their growth rate in height, we measured the height and diameter of 18 to 43 individuals per species. Height was regressed on diameter to obtain an equation that allowed us to estimate height based on dbh (average $r^2 = 0.81$, range = 0.65 to 0.91). Hence, plants < 300 cm in the pre-logging measurement had only height growth rate calculated, regardless whether they had dbh measured in later years.

To evaluate the effect of logging and time on growth rates we used a GLM repeated measured ANOVA with time and logging as factors and growth rate as the dependent variable. To test the effect of light and forest structure on overall growth rates we used one-way ANOVA followed by Tukey post-hoc test, with crown position or forest structure as factor and overall growth rate as depend variable. The crown position level used for the analysis corresponded to the first post-logging year measurement for each individual.

Because of small sample sizes (< 5 individuals in one treatment) statistical analyses could not be done for *B. guianensis* densities and for densities of individuals ≥ 300 cm of *H. courbaril* and *D. odorata*. Similarly, the diameter growth rates of *B. guianensis*, *H. courbaril*, and *D. odorata* and the height growth rates of *J. copaia* were not calculated due to small sample size. $\ln(x+1)$ transformation was necessary for increasing variances homogeneity and normality of the variables density and growth rates. Statistical analyses were performed with the IBM SPSS 19.0 (New York) software.

Results

Forest structure

Transects did not differ in the frequency distribution of forest-phases before logging (Chi-square = 2.1, $p = 0.35$). As it was expected logging resulted in more plots being classified in the gap and intermediate phases in the logged transects than in the unlogged ones (Chi-square = 302.4, $p < 0.001$). Although these differences were maintained even 6 years after logging (Chi-square = 7.6, $p = 0.02$), there was a continuous shift of plots from the gap- to the building- and mature-phases (Fig. 1).

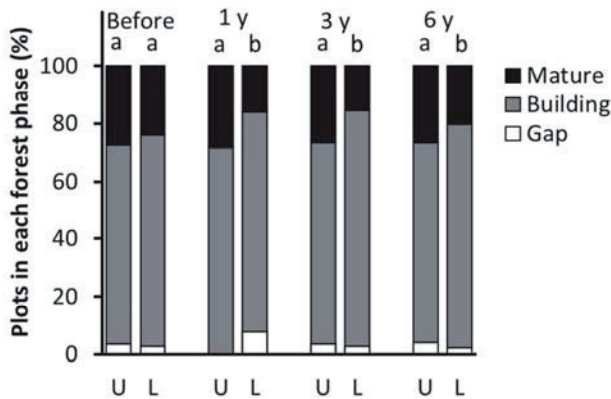


Fig. 1. Frequency of forest phases (gap, building, and mature) between unlogged (U) and logged (L) plots, before and 1, 3 and 6 years after harvesting in the Tapajós National Forest, the Eastern Amazon, Brazil. Letters indicate differences between treatments in each measurement.

Density

Density of plants smaller than 300cm varied tremendously among species. For example, the long-lived pioneer (LLP) species *Bagassa guianensis* had no regeneration before logging while the partially shade tolerant (PST) species *Carapa guianensis* was the most abundant species with 1.63 individuals per 100 m² (Fig. 2). The effect of logging varied also among species (Table 2). Logging had a positive effect on the densities of *Jacaranda copaia* and *Symphonia globulifera*, a negative effect on the density of *C. guianensis*, and no effect on the density of *Hymenaea courbaril*, *Dipteryx odorata*, and *Manilkara huberi*. Densities also varied through time for all species but *H. courbaril*. There was a significant interaction between treatment and time for all species, except *D. odorata* (Table 2), indicating that the effect of treatment varied through time (Fig. 2). Concerning plants larger than 300 cm, only the density of *J. copaia* was affected by logging, time, and the time-treatment interaction (Table 2), having a peak in density in the 3rd year after harvesting.

In the first post-logging year *J. copaia*, *H. courbaril*, *D. odorata*, *S. globulifera*, and *M. huberi*, increased their recruitment rates, while *C. guianensis* diminished its recruitment rate (Fig. 3). On the other hand, mortality rates were higher for *J. copaia*, *D. odorata*, *C. guianensis* and, *S. globulifera* and lower for *H. courbaril* and *M. huberi*. In general, both recruitment and mortality rates decreased through time for *J. copaia*, *D. odorata*, *S. globulifera*, and *M. huberi* (Fig. 3). As *B. guianensis* had zero counts in 3 out of 8

measurements, the increase in recruitment observed in the logged area in 2004 could not be calculated. No recruitment was observed in 2006 and 2009 (Fig. 3), and there was a continuous decrease in number of individuals from 2006 to 2009 due to mortality.

RIL had both favourable as well as negative impacts on the individuals over 300 cm. Recruitment rate of *J. copaia* was 44.3% in the logged area and zero in the control, during the third post-logging year. In contrast, mortality rate was higher in the logged areas for *C. guianensis* (18%) and *S. globulifera* (18.8%) compared to the unlogged areas (0% mortality). Similar mortality and recruitment rates were found in both treatments for *M. huberi*. There were no sufficient data for *B. guianensis*, *H. courbaril* and *D. odorata* to do the same analysis.

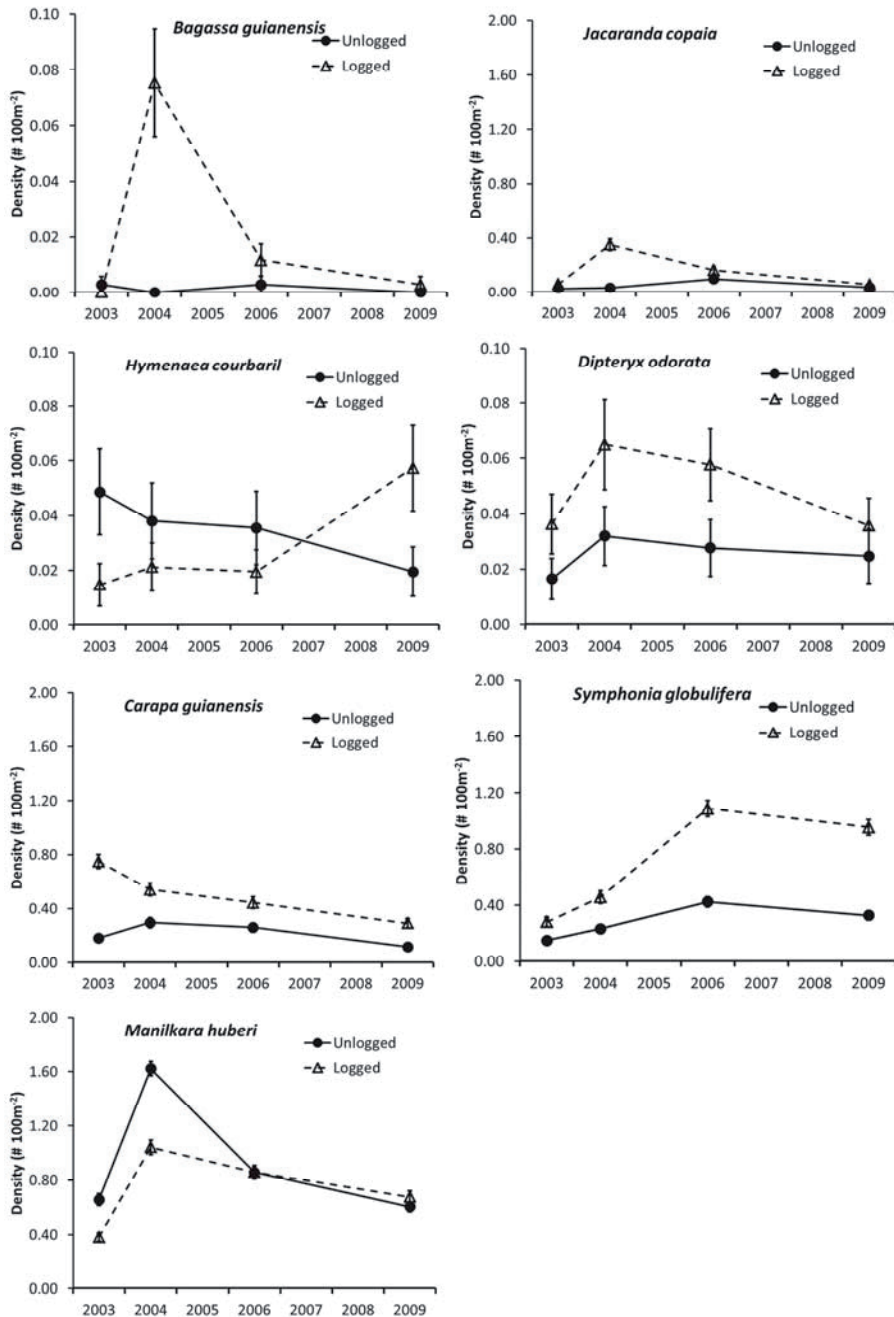


Fig. 2. Density (individuals/100m² \pm 1.0 SE) of individuals < 300 cm of seven tree commercial species in the Tapajós National Forest, Brazil before and 1, 3 and 6 years after logging. Maximum 'y' axis value is 0.10 for *Bagassa guianensis*, *Hymenaea courbaril*, and *Dipteryx odorata* and 2.0 for *Jacaranda copaia*, *Carapa guianensis*, *Symphonia globulifera*, and *Manilkara huberi* (back-transformed data).

Table 2

Effect of logging on the density of commercial tree species in the Tapajós National Forest, Brazil. Data were analysed with Repeated Measures ANOVA. Due to small sample sizes, no analyses were done for *B. guianensis*. F values and p values are given (ns: non-significant. *: $0.01 \leq p < 0.05$. **: $0.001 \leq p < 0.01$. ***: $p < 0.001$).

Species	Individuals < 300 cm			Individuals \geq 300 cm		
	Treatment	Time	Time x Treat.	Treatment	Time	Time x Treat.
<i>J. copaia</i>	19.2***	19.7***	18.5***	10.1**	8.6**	7.7**
<i>H. courbaril</i>	0.2ns	0.7ns	8.3***	-	-	-
<i>D. odorata</i>	3.0ns	3.7*	0.8ns	-	-	-
<i>C. guianensis</i>	23.6***	23.0***	12.8***	2.7ns	0.4ns	1.7ns
<i>S. globulifera</i>	32.5***	88.4***	17.7***	1.6ns	0.7ns	1.6ns
<i>M. huberi</i>	3.2ns	97.5***	14.2***	0.0ns	0.7ns	0.1ns

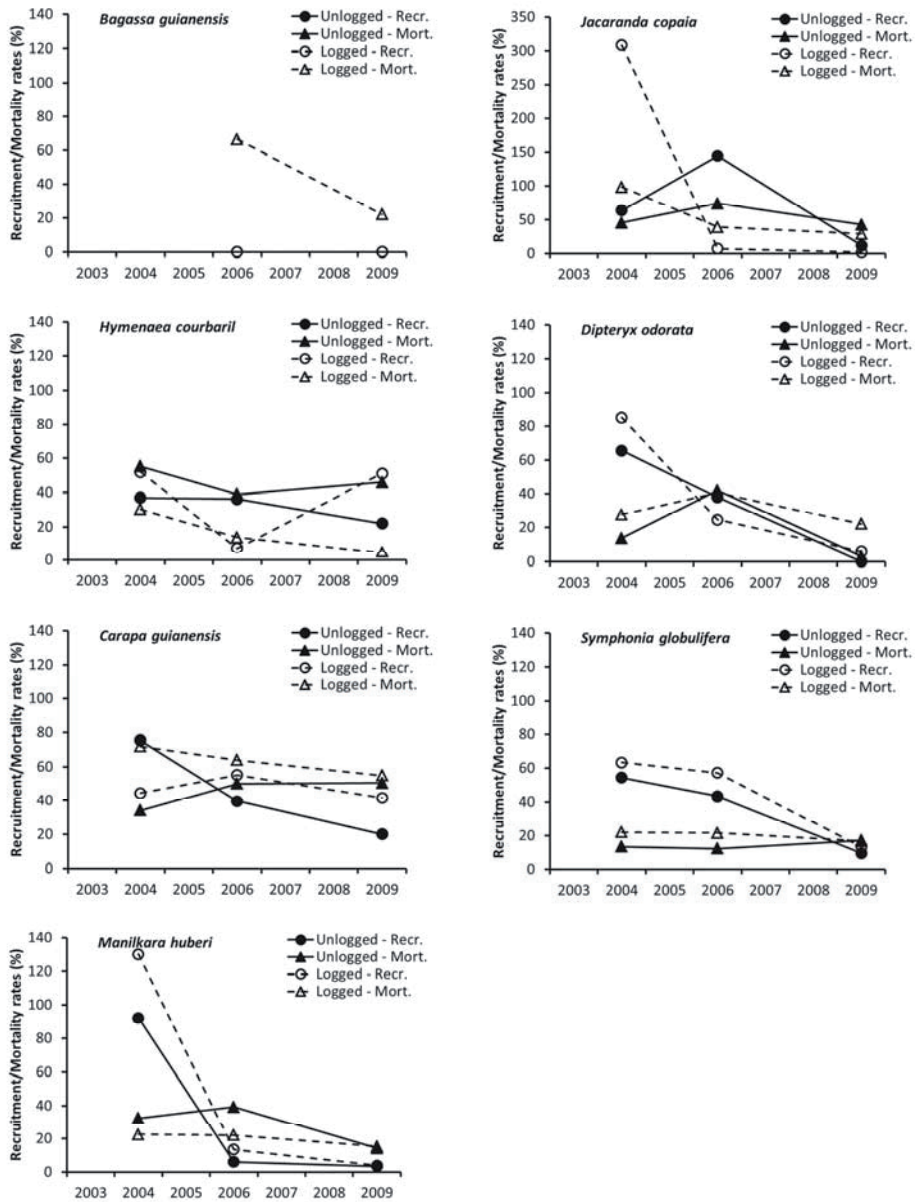


Fig. 3. Recruitment and mortality rates (in percentage) of individuals <300 cm of seven tree commercial species in an unlogged and in a logged area in the Tapajós National Forest, Brazil. Please note that axis Y is different for *Jacaranda copaia*.

Growth rates

All species in the treated area showed higher growth rates in the first year after logging, except for height growth in *M. huberi* (Fig. 4). In terms of height growth rate, logging had an effect only on the growth rate of *S. globulifera*, while the height growth rates of *C. guianensis* and *M. huberi* varied through time (Table 3). Concerning dbh growth rates, logging only had a positive effect on *C. guianensis*. Dbh growth rates changed through time for *C. guianensis* and *M. huberi* and because of treatment and time for *J. copaia* and *C. guianensis* (Table 3).

Table 3

Effect of logging on the height and dbh growth rates of commercial timber species in the Tapajós National Forest, Brazil. Data were analysed with Repeated Measures ANOVA. F values and p values are given (ns: non-significant. *: $0.01 \leq p < 0.05$. **: $0.001 \leq p < 0.01$. ***: $p < 0.001$). Only species with > 5 individuals per treatment were included in the analyses.

Species	Height			Dbh		
	Treatment	Time	Time x Treat.	Treatment	Time	Time x Treat.
<i>J.copaia</i>	-	-	-	0.9ns	2.3ns	4.2*
<i>C.guianensis</i>	4.2ns	18.8***	0.8ns	4.8*	6.5**	6.8**
<i>S.globulifera</i>	4.2*	2.2ns	0.6ns	1.6ns	0.1ns	0.6ns
<i>M.huberi</i>	1.4ns	3.9*	0.3ns	2.7ns	9.5**	1.83ns

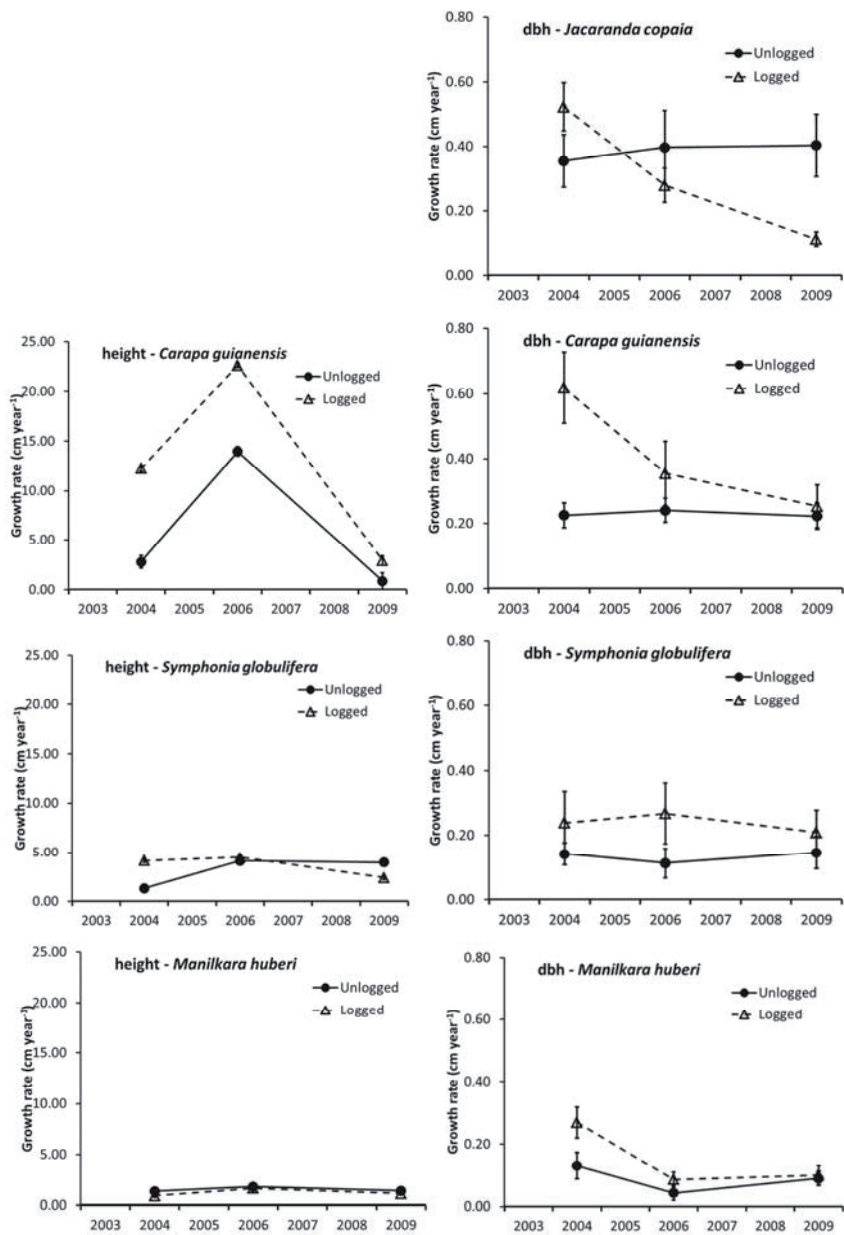


Fig. 4. Height and dbh growth rates (cm/year \pm 1SE) of *Carapa guianensis*, *Symphonia globulifera*, and *Manilkara huberi* and dbh growth rate for *Jacaranda copaia* in the Tapajós National Forest, east Amazon (back-transformed data).

Plants growing in the gap-phase plots had higher height growth rates than plants growing in building- or mature-phase plots (ANOVA, $F_{2,2980} = 33.3$, $p < 0.001$). However, the forest phase did not show an effect on dbh growth rates (ANOVA, $F_{1,364} = 0.9$, $p = 0.33$). Crown position had positive effects on height and dbh growth rates (Fig. 5). The higher the crown position, the faster the plant had grown in height (ANOVA, $F_{3,2979} = 148.4$, $p < 0.001$) and dbh (ANOVA, $F_{3,362} = 26.1$, $p < 0.001$).

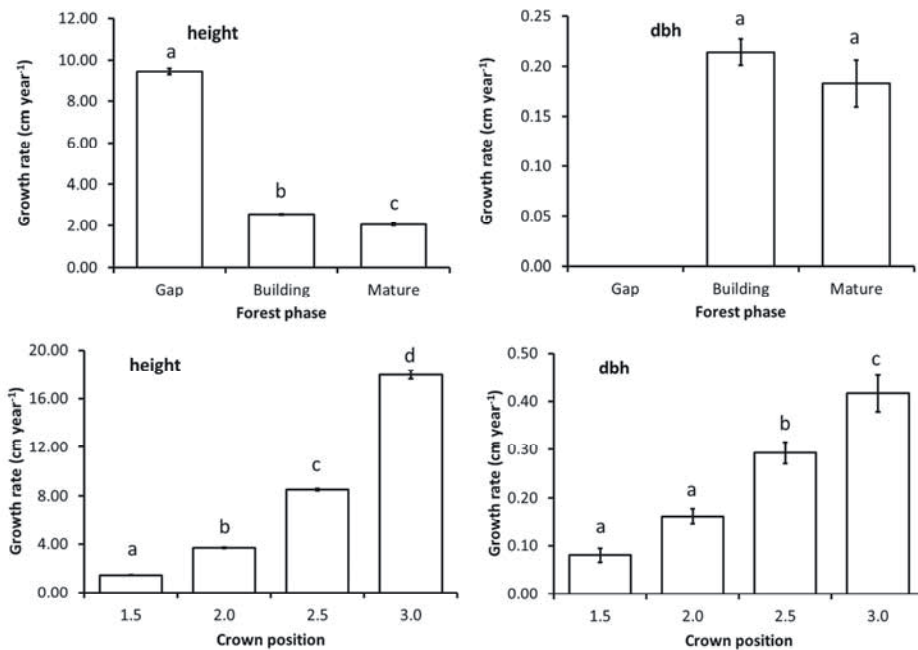


Fig. 5. Effects of forest phase on the height and dbh growth rates and effects of crown position on the overall height and dbh growth rates over all species in the Tapajós National Forest. Letters indicate the statistical differences ($p < 0.05$) applying one-way ANOVA followed by Tukey post-hoc test.

Discussion

Forest structure

The extraction of $22\text{m}^3\text{ha}^{-1}$ of timber from logged areas resulted in a higher frequency of plots in the gap- and intermediate- forest phase when compared to unlogged areas (Fig. 1). These differences are likely to disappear through time at different rates depending on forest phase. It is expected that the shift from gap-phase to building-phase usually occurs rapidly due to the increased recruitment and growth rates of pioneer species (Brokaw, 1985) in the

first years after the disturbance event. Changes from building-phase to mature-phase plots will occur at a much slower pace mainly, either because large commercial trees (≥ 45 cm in dbh) had been logged, or because the remaining trees had not reached a diameter of 45 cm 6 years after logging. Silva et al. (1995; 1996), in a nearby area, observed increased growth rates only in the first three years after logging. After that, growth rates diminished toward the same levels observed in unlogged forests. Even 28 years after logging, most of the logged species did not recover the harvested volume of timber (Reis et al., 2010). Slow growth rates and volume recovered have been observed in other Amazonian forests. Such forests probably will not reach the same pre-logging yield volumes, considering the current harvested volumes and cutting cycles of 30 years (Valle et al., 2007; Sist and Ferreira, 2007). These results indicate that forest structure and timber volume may not recover at the same pace.

Density

Most of the harvested Amazonian tree species have low densities (< 1 adult tree per ha) and scarce regeneration (Schulze et al., 2008a). *B. guianensis* is typical of long-lived pioneers (LLPs), having low adult tree densities (Table 1) and extremely low gap-dependent regeneration (only one individual was observed in the 4.74 ha sample in this study). The second LLP species, *J. copaia*, is also a species with low density and gap-dependent regeneration spread all over the Amazon (Maues, 2006), and there are reports that this species also faces regeneration problems (Mostacedo and Fredericksen, 1999). Both *B. guianensis* and *J. copaia* had their densities strongly increased by logging. Nevertheless, densities diminished through time, returning to pre-logging levels 6 years after logging due to high mortality rates and a steep decrease in their recruitment rates (Fig. 3). Swaine and Agyeman (2008) describe a similar pattern for pioneer species in a tropical forest of Ghana. Positive effects of RIL can also be seen in individuals over 300 cm height of *J. copaia* (Table 2).

The partially shade tolerant (PST) species *C. guianensis* has high densities, elevated aggregation (Klimas et al., 2007; Tonini et al., 2009), and rich regeneration but also presents high mortality due to fungi diseases and seed predation, as observed by Henriques and Sousa (1989) in the Eastern Amazon. Such pattern may also be observed in our study. Excessive light penetration on its understory regeneration probably affected seedling survival. Similar negative effects of RIL on the regeneration of PST and totally shade tolerant species (TST) species was also reported by Toledo-Aceves et al. (2009) in Selva Maya, Mexico.

Regarding the other two PST species, *D. odorata* and *H. courbaril* had low regeneration density in the studied area, as in other Amazonian locations (Gómez, 2011).

Despite an increase in recruitment rate of *D. odorata* in the first year after harvesting, RIL did not affect its density. Herrero-Jáuregui et al. (2011), in the same national forest, found no effects of logging on the recruitment of *D. odorata*. Although low numbers of individuals, *H. courbaril* increased its density in the logged areas by year six after logging. Poor regeneration is an issue for *H. courbaril* in Bolivian forests and, according to Mostacedo and Fredericksen (1999), solutions for improving it are costly. However, in Tapajós National Forest there is no clear evidence whether the species is facing regeneration problems, although it is also not a common species.

TST species had different density responses. *S. globulifera*, regardless of being rare (Carneiro et al., 2009), and having the lowest density of adults among the studied species (Table 1), showed larger densities in logged areas than in the unlogged ones (Fig. 2). This was mainly because of the high recruitment rates during the first 3 years after logging (Fig. 3). In contrast with the LLP species, *S. globulifera* density did not decrease through time, probably because it had one of the lowest mortality rates observed in this study. Finally, logging had no effects on the *M. huberi* density. The first post-logging year increase in density might be happened due to mass fructification as the same pattern was also observed in the unlogged area (Fig. 2).

Growth rates

A small number of individuals were able to survive during all measurements. Because of this, diameter growth rates of *B. guianensis*, *H. courbaril*, and *D. odorata* and the height growth rates of *J. copaia* were not obtained. Logging had much less effect on growth rates than expected (Fig. 4). Only *S. globulifera* grew faster in height in the logged areas than in the unlogged ones (Table 3). Shade-tolerant species may keep slow growth rates for long periods before starting faster growth due to canopy openings (Brenes-Arguedas et al., 2011). Dbh growth rates of *J. copaia* decreased probably because of competition with *Cecropia* spp. individuals, commonly found in Tapajós, which might have taken advantage of larger logging gaps. On the other hand, *C. guianensis* was the unique species presenting positive growth in dbh, not outcompeted by *Cecropia*.

The changes caused by RIL on the forest structure had a positive effect on the height and dbh growth rates for all the species (Fig. 5). A higher light incidence in plots converted into gap-phase made it possible that individuals attained higher growth rates, which has been observed in several other studies in unmanaged (Denslow, 1987) and managed forests (Felton et al., 2006; Swaine and Agyeman, 2008; Verwer et al., 2008). Our results corroborate again

this pattern, showing that individuals with higher crown position higher height and dbh growth rates (Fig. 5).

Silvicultural implications

Regeneration of commercial species is a pre-requisite for assuring enough timber in future cutting cycles. Depending on the intensity, logging may be an efficient tool for improving recruitment and growth rates of valuable tree species (Fredericksen and Putz, 2003). Nevertheless, such favourable effects usually disappear over time due to forest resilience (Silva et al. 1995; Swaine and Agyeman, 2008). Furthermore, the desirable effects of logging alone may not be sufficient for increasing regeneration. In this sense, post-harvesting silvicultural treatments would be a requirement for guaranteeing that the increased number of recruits achieves harvestable sizes for future harvests.

According to our mid-term assessment in Tapajós National Forest, recruitment rates were generally augmented after logging. Seemingly, no silvicultural treatment is needed for triggering germination, but germination might be improved by applying top soil removal when managing light demanding species (Fredericksen and Pariona, 2002; Peña-Claros et al., 2008a). It could work especially for increasing recruitment rates of *B. guianensis*. Nevertheless, LLP species had lower recruitment rates from the third post-harvesting year onwards, likely due to reduced amounts of available light as plots moved from the gap- to the intermediate forest phase (Fig.1). Although individuals of *J. copaia* with a height over 300 cm had a significant increase in density, they did not present a good growth performance. In the Tapajós National Forest seedlings and saplings compete more with pioneer species (e.g. *Cecropia* spp.) than with covering vines in gaps (J.C. Lopes, personal observation). Perhaps the decrease in *J. copaia* dbh growth rate was due to this competition; and therefore, *J. copaia* and even the sparse individuals of *B. guianensis* may benefit from liberation treatments. This treatment would be applied around two years after logging with repetitions through time as needed the two LLP species. Such silvicultural treatments could also be applied on the shade-tolerant species, considering that most of them had higher recruitment rates after RIL. Although *C. guianensis* diminished in density, it had a positive response in dbh growth rate that could be enhanced by saplings liberation. *M. huberi* and *S. globulifera* may also receive the same treatment to assure higher dbh growth rates for a longer time. However, further studies on assessing cost-benefit relations of applying scarification or liberation on saplings are needed.

Conclusions

In this research we found that although the effects of RIL on the forest structure persist 6 years after logging, these changes in light incidence are not sufficient to maintain the higher recruitment rates observed during the first year after logging. Consequently, for most of the studied species (5 out of 7) there was a decrease in density and growth rates through time after logging. These results suggest that just the application of RIL is not enough to promote regeneration of commercial species, and that RIL should probably be followed by the application of other silvicultural treatments, such as liberation from competing vegetation, to enhance the survival and growth rates of commercial species regeneration.

Chapter 4

Post-harvesting silvicultural treatments in logging gaps: a comparison between enrichment planting and tending of natural regeneration

Gustavo Schwartz, José C. A. Lopes, Godefridus M. J. Mohren, Marielos Peña-Claros

(Accepted for publication in Forest Ecology and Management)



Anacardium giganteum (Anacardiaceae)

Abstract

Despite of many management improvements in the last decades, long-term assessments show that future volume yields will decrease if current harvesting volumes and cutting cycles are maintained. One way to mitigate this problem is the application of post-harvesting silvicultural treatments to increase the number of valuable trees. In this study we compare the treatments of tending naturally established seedlings/ saplings of commercial species in logging gaps with enrichment planting + tending seedlings of commercial species. The research was carried out in the forest management area of the forestry company Orsa Florestal in Jari Valley, eastern Amazon, Brazil. We sampled 64 2-years old logging gaps with an average size of 427.2 m². Thirty-four gaps were used for the planting + tending, 15 for the tending, and 15 for the control treatment. The tending treatment showed lower mortality rate, higher growth rate, and required less liberation from overstorey plants and lianas than the other two treatments. Five out of 10 species positively responded to silvicultural treatments, the long-lived pioneers *Goupia glabra* and *Laetia procera*, and the partially shade tolerant *Dinizia excelsa*, *Tachigali myrmecophila*, and *Trattinnickia* sp. Based on these results we recommend tending in areas with sufficient natural regeneration of commercial species. Enrichment planting + tending should only be used with species having high initial growth rates and high commercial value.

Key words: Silviculture; Jari; eastern Amazon; forest management; tropical forests

Introduction

The world consumption of timber and non-timber products from tropical forests has been constantly increasing (SFB/IMAZON, 2010; Shearman et al., 2012), which demands not only a higher production but substantial improvements in forest management. So far some progress has been made, such as government logging restrictions and the application of reduced-impact logging (RIL) consisting in careful planning of pre- and post-harvesting operations (Zarin et al., 2007). It has also been demonstrated that such forest management advances are efficient for conserving forest structure, species diversity, and for maintaining ecological services (Pereira et al., 2002; Azevedo-Ramos et al., 2006; Sebbenn et al., 2008; Imai et al. 2009). There is, however, still much uncertainty on whether these forest management improvements are sufficient to assure future timber production, i.e. the same volume yields of the same tree species harvested during the first cutting cycle. Simulations of future scenarios predict that the present technical advances in tropical forest management do not guarantee the same current yields of timber volume using 30-years cutting cycles (Dauber et al. 2005; Azevedo, 2006; Sist and Ferreira, 2007; Valle et al., 2007). Some possible alternatives to mitigate the problem include: to change the set of harvested species towards the more light-wooded species (Reis et al., 2010), to diminish the timber volume extracted, to enlarge logging cycles (Huth and Ditzer, 2001; Hawthorne et al., 2012), and to apply silvicultural treatments on future crop trees (Dauber et al., 2005). A complementary option is to manage logging gaps to increase the density of individuals of commercial species aiming to harvest them during the third and fourth cutting cycles. There are different silvicultural options to achieve this goal: the promotion of the natural establishment of the regeneration through top soil removal (Fredericksen and Pariona, 2002), tending the naturally established regeneration by reducing competition from lianas and other trees (Pariona et al., 2003; Park et al. 2005), and enrichment planting (Schulze, 2008; Doucet et al., 2009; Keefe et al., 2009).

Tending the natural regeneration of commercial species and enrichment planting are potentially complementary post-harvesting silvicultural treatments. When the availability of natural regeneration is sufficient, tending naturally established seedlings may be the most ecologically and economically viable alternative (Pariona et al., 2003; Schulze, 2008; Schwartz et al., 2012). Tending would attenuate the negative effects of liana invasion and competition of pioneers and non-commercial species, diminishing mortality and increasing growth rates of desirable species. The post-harvesting successional process in logging gaps might, however, result in poor regeneration of commercial species, which ultimately might impede sustainable cutting cycles (Fredericksen and Putz, 2003). Insufficient regeneration of

commercial species along post-harvesting succession has been reported even in carefully managed tropical forests (Mostacedo and Fredericksen, 1999; Park et al., 2005; Doucet et al., 2009), which imposes a silvicultural challenge for assuring future timber yields. Therefore, under a shortage of regeneration, enrichment planting in logging gaps may be an acceptable alternative (D'Oliveira, 2000a; Lopes et al, 2008; Keefe et al, 2009; D'Oliveira and Ribas, 2011), although it can be a more costly silvicultural treatment (Schulze, 2008; Bais, 2012).

The objectives of this study were to assess the mortality and growth rates of seedlings and saplings of commercial tree species growing in logging gaps in the Eastern Brazilian Amazon subjected to two silvicultural treatments: (1) tending naturally established individuals and (2) enrichment planting plus tending.

Materials and methods

Study area

The study was carried out in the forest management area of the forestry company Orsa Florestal S.A., more specifically in the logging compartment of 2004. The management area is located at Jari Valley, municipality of Almeirim (01°09'S and 52°38'W), Pará state, Brazil. It has a total area of 545,535 ha, with a mean altitude of 150 masl. The average precipitation is 2,200 mm, with a dry season from June to August, and annual average temperature of 26°C. Soils are mostly yellow latosols. The vegetation is mainly composed by ombrophilous dense forest or "terra firme" forest. Savannas and floodplains are also found in a smaller proportion (Azevedo, 2006; Alves and Miranda, 2008). The managed area of natural forests was certified using the FSC standards in 2004 (Orsa Florestal, 2012). The company harvests timber from 27 species, with an average harvesting intensity of 25 m³ ha⁻¹. Harvesting is done using RIL techniques.

Experimental design

In March 2006, 64 2-year old logging gaps created during logging operations were randomly chosen in the 2004 logging compartment. Gap area was estimated assuming an ellipsoidal shape, having its minor and major axes length measured. The border of the gap was defined by the vertical projection of the canopy opening. We randomly assigned the 64 gaps to three treatments: 34 gaps were used for enrichment planting, 15 gaps for tending of existing regeneration, and 15 for control. In the 34 gaps selected for enrichment planting, hereafter called "planting + tending", we removed all the existing vegetation by slashing it down. Seedlings of 10 commercial species were planted to fill available space in logging

gaps (i.e., part of the gaps were occupied by residual branches of felled trees). The planted seedlings were produced in nurseries with seed collected in the forest management area of Orsa Florestal. In total 1520 seedlings were planted (152 individuals per species), following a North-South orientation, and with a spacing of 2.5 x 2.5 m. The sequence of planting consisted in sets of 10 randomly chosen individuals (one per species). In average, 44.7 seedlings were planted per gap (range: 22-69). All plants were tagged, mapped and measured in height (plants < 300 cm) or dbh (individuals ≥ 300 cm) twice per year from March 2006 to March 2008, and then yearly until March 2010. Additionally the crown position of each plant was assessed according to Clark and Clark (1992): 1.5 (low indirect light incidence on the plant), 2.0 (indirect light), 2.5 (lateral direct light), and 3.0 (overhead light incidence). Finally, in each evaluation liberation treatments were applied when needed. The liberation consisted in freeing focal plants from lianas and other plants by removing them from a radius of 50 cm around the focal plant. Lianas and branches of higher individuals than the focal plant were also cut with a machete. No individuals belonging to the experiment were cut (entirely or partially) for benefitting another one. Plants being tended had their crown position measured, right before and right after the application of the liberation treatment. We also recorded the effort done during treatment application (i.e. counted the number of plants that were tended per gap).

In September 2006 we searched, identified and marked seedlings and saplings of commercial or potentially commercial tree species (according to the list of species traded by Orsa Florestal) in each one of the 30 remaining gaps. The amount of individuals per gap varied considerably, so that in some gaps all available individuals were assessed, while in others only part of the regeneration was included in the experiment. An average 27.7 individuals per gap (range: 14-41) were evaluated (Table 1), totalizing 832 sampled plants belonging to 50 species. Like in the planting + tending experiment each individual was tagged, mapped and measured in height (plants < 300 cm) or dbh (individuals ≥ 300 cm) and had its crown position evaluated. We randomly picked half (15) of the sampled gaps for applying the same liberation treatments to the marked individuals when needed as described for the planting + tending treatment. This treatment is referred as “tending” hereafter. In the other 15 gaps individuals were evaluated as indicated before but did not received any silvicultural treatment. Hereafter this treatment is referred as “control”. Plants of both treatments were measured twice per year from September 2006 to September 2008, and once a year until September 2010.

Table 1

Description of the initial conditions in logging gaps in the managed forests of Orsa Florestal in Jari Valley, Brazil. Data are average \pm SE. Letters indicate post-hoc differences (Tukey test) for gap size and density and pairwise comparisons for initial height.

	Control	Tending	Planting + tending
Gap size (m ²)	424.4 \pm 25.8 ^a	481.4 \pm 26.8 ^a	433.7 \pm 23.1 ^a
Density (number of individuals m ⁻²)	0.070 \pm 0.004 ^a	0.056 \pm 0.004 ^a	0.110 \pm 0.006 ^b
Total number of individuals sampled	436	396	1520
Total number of species sampled	34	39	10
Initial height (cm)	176.6 \pm 6.7 ^b	198.8 \pm 7.1 ^b	45.1 \pm 0.8 ^a

Study Species

The ten planted species in the planting + tending treatment were: the long-lived pioneer (LLP) *Bagassa guianensis*; the partially shade-tolerant (PST) *Anacardium giganteum*, *Brosimum parinarioides*, *Carapa guianensis*, *Dinizia excelsa*, *Hymenaea courbaril*, *Platymiscium filipes*, and *Tabebuia serratifolia*; and the totally shade tolerant (TST) *Mezilaurus lindaviana* and *Vouacapoua americana*. The 15 most common species sampled and assessed in the control and tending treatments were: the LLP *Schefflera morototoni*, *Goupia glabra*, *Jacaranda copaia*, *Jacaranda* sp., and *Laetia procera*; the PST *B. parinarioides*, *D. excelsa*, *Humiria balsamifera*, *Hymenolobium flavum*, *Parkia reticulata*, *Qualea albiflora*, *Tachigali myrmecophila*, *Trattinnickia rhoifolia*, *Trattinnickia* sp., and *Vochysia obscura*. A total of 55 species were assessed in the three treatments.

Data analysis

Gap size and total density were compared using one-way ANOVA, with treatment as factor (Table 1). Initial height was compared using a GLM univariate ANOVA with treatment as the fixed factor, Ln (initial height) as the dependent variable, and gaps as a random factor (Table 1). Mortality rate was calculated for each measurement and gap with the formula: $m = (\ln n_0 - \ln S_t)/t$, where n_0 is the number of individuals in the previous measurement and S_t the number of survivors, t is the time elapsed between two given measurements (Losos and Lao, 2004). Mortality rates were analysed using the GLM repeated measures ANOVA, with time and treatment as factors and mortality rate as the dependent variable.

The overall growth rate was calculated at the individual level for individuals that remained alive over all measurements. The individual height measurements were regressed

over time, using all available measurements, and then the slope of the linear regression was multiplied by 365 days for getting the annual height growth rate. Plants with negative height growth rates (broken) were maintained in the analyses. Individuals that started being measured in height and became ≥ 300 cm in height had their dbh measured in later measurements. Consequently, to be able to calculate their growth rate in height, we measured the height and diameter of 18 to 43 individuals per species. Height was regressed on diameter to obtain an equation that allowed us to estimate height based on dbh (average $r^2 = 0.85$, range = 0.74 to 0.94). We analysed the effect of silvicultural treatments on height growth rate using a GLM univariate ANCOVA with a full factorial model (Field, 2005) to increase precision of the statistical tests (Steel and Torrie, 1981) and avoid treatment bias. In the ANCOVA we used treatment as the fixed factor, Ln (overall growth rate + 1) as the dependent variable, gap as a random factor, and initial height as the covariate. The same model was applied to test the effect of treatment on species grouped according to their functional groups and on species specific growth rates. These analyses were done only for functional groups or species with at least five individuals in two of the three treatments. Finally, we used the same model to test the effect of treatments on the growth rate of the dominant individuals: the most dominant one, the 3-, 5-, and 10-most dominant individuals, since these individuals have higher chances to become adults and contribute to future cutting cycles. The model to compare the effect of treatments on the growth rate of the single most dominant individual did not include gaps as a random factor, since there was only one individual per gap. Statistical analyses were performed with the IBM SPSS 19.0 software.

The effort applied during tending was calculated per gap and per treatment, as the ratio between the number of liberated plants over the number of individuals alive at a given measurement. Then the tending effort ratio was analysed using the GLM repeated measures ANOVA, with time and treatment as factors and the ratio of treated plants as the dependent variable. The number of times that each individual was liberated was also counted, which ranged from zero to six (maximal number of measurements). The number of liberation events was analysed using one-way ANOVA with treatment as factor and number of times that each individual was treated as the dependent variable.

Results

Logging gaps and sampled species

The 64 gaps used in this study ranged in size from 155.5 to 907.1 m² (average = 427.2 \pm 16.0 m² SE; median = 415.8 m²), with treatments having similar gap sizes (ANOVA, $F_{2,61} =$

1.8, $p = 0.177$). Treatments differed in initial density of seedlings and saplings (ANOVA, $F_{2,61} = 9.0$, $p < 0.001$), due to the greater number of individuals per gap in the planting + tending treatment (Table 1). Initial height also varied among treatments (ANCOVA, $F_{2,2288} = 1085.5$, $p < 0.001$) because of the smaller height of the planted seedlings (Table 1). In both control and tending treatments the most abundant species sampled were the LLP *L. procera* and *G. glabra*, and the PST *Trattinnickia* sp. and *D. excelsa*.

Mortality and growth rates

Mortality varied with treatment (Repeated measures ANOVA, $F_{2,61} = 10.0$, $p < 0.001$), being mortality the lowest in the tending treatment (Fig. 1). Mortality also increased through time (Repeated measures ANOVA, $F_{4,270} = 5.8$, $p < 0.001$) but the effect of treatment did not differ over time (Repeated measures ANOVA, for treatment x time: $F_{9,270} = 1.6$, $p = 0.104$).

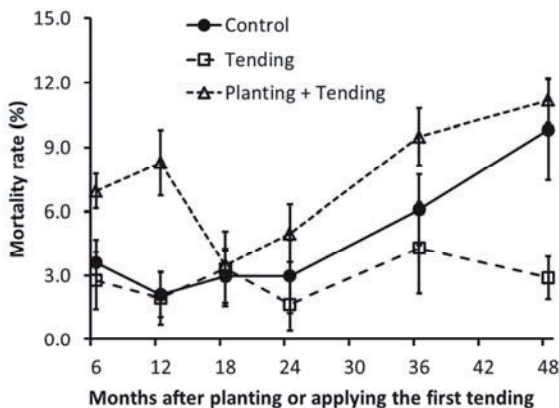


Fig. 1. Mortality rates (percentage \pm SE) of seedlings and saplings of commercial tree species growing in logging gaps subjected to three different treatments in the managed forests of Orsa Florestal in Jari Valley, Brazil.

When the most dominant individual is considered, treatments did not differ on average height growth rates (ANCOVA, $F_{2,60} = 1.0$, $p = 0.381$, Fig. 2). Treatments differed, however, when a larger number of dominant individuals was considered (ANCOVA, for the 3 most dominant: $F_{2,127} = 28.5$, $p < 0.001$; for the 5 most dominant: $F_{2,255} = 39.9$, $p < 0.001$; and for the ten most dominant; $F_{2,575} = 36.1$, $p < 0.001$) (Fig. 2). When all plants were considered in

the analysis treatments also differed from each other (ANCOVA, $F_{2,1749} = 16.7$, $p < 0.001$, Fig. 2).

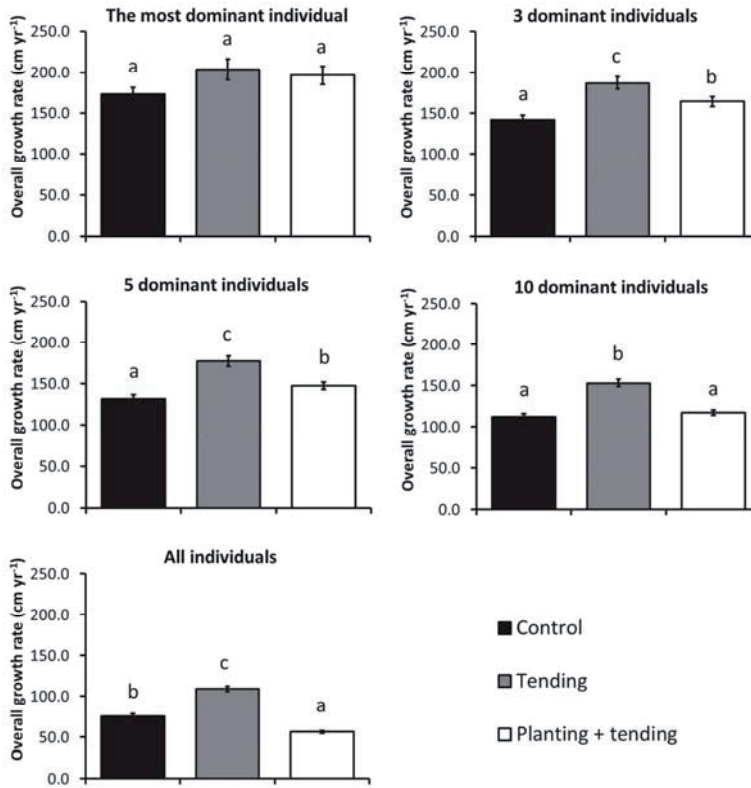


Fig. 2. Overall height growth rate (average \pm SE) of seedlings and saplings of commercial tree species growing in logging gaps subjected to three treatments: control, tending, and planting + tending in the managed forests of Orsa Florestal in Jari Valley, Brazil. Comparisons were done between the most dominant individual per gap, the three, five, and ten most dominant individuals as well as all assessed plants. Letters indicate pairwise comparisons.

The LLP species in general showed higher overall growth rates in tending and planting + tending than in the control treatment (Table 2). The PST species had the highest overall growth rate in tending, with similar growth rates in the other two treatments (Table 2). Tending was more efficient than planting + tending for TST species, other comparisons were not possible due to small sample sizes (Table 2). Of the 10 species we could evaluate the treatment effect, 40% of them (2 LLP and 2 PST) positively responded to silvicultural treatments, having higher overall growth rates in tending or planting + tending gaps than in

control ones. The other species had similar growth rates in the different treatment combinations. Only *D. excelsa* had enough individuals in all treatments to allow a comparison among them (Table 2). This species had higher overall growth rates in tending (84.0 cm year⁻¹) and planting + tending (76.6 cm year⁻¹) than in control (54.7 cm year⁻¹).

Table 2

Effects of silvicultural treatments on overall average height growth rates of the species grouped in functional groups and of the most common species growing in different treatments in the managed forests of Orsa Florestal in Jari Valley, Brazil. Only species with at least five individuals in two of the treatments were included (10 out of 55). Treatments are control (C), tending (T), and planting+ tending (P+T). Data were analysed using ANCOVA (gap as a random factor and initial height as the covariate) to correct for initial height differences among treatments. LLP=Long-lived pioneer; PST=Partially shade tolerant; and TST=Totally shade tolerant. F and p values are given (ns: non-significant, *: $0.01 \leq p < 0.05$, **: $0.001 \leq p < 0.01$, ***: $p < 0.001$).

Species	Functional Group	C vs. T	C vs. P+T	T vs. P+T
-	LLP	20.3***	37.3***	0.0 ns
-	PST	13.8***	1.4 ns	3.7ns
-	TST	-	-	15.8*
<i>Goupia glabra</i>	LLP	20.3***		
<i>Jacaranda copaia</i>	LLP	0.0 ns	-	-
<i>Jacaranda</i> sp.	LLP	2.1 ns	-	-
<i>Laetia procera</i>	LLP	35.2***	-	-
<i>Brosimum parinarioides</i>	PST	-	1.0 ns	-
<i>Dinizia excelsa</i>	PST	14.4**	52.5***	2.6 ns
<i>Humiria balsamifera</i>	PST	0.2 ns	-	-
<i>Qualea albiflora</i>	PST	0.0 ns	-	-
<i>Tachigali myrmecophila</i>	PST	2.4ns	-	-
<i>Trattinnickia</i> sp.	PST	5.9*	-	-

The effort of tending

When the tending treatment was established, $54.5 \pm 6.1\%$ (SE) of the plants per gap were liberated from competitors (for $13.3 \pm 2.8\%$ of the plants were liberated from overtopping plants; $33.0 \pm 5.4\%$ from lianas, and $8.3 \pm 2.6\%$ from both). The effort of tending after the experiment was established was larger in planting + tending than in tending (Repeated measures ANOVA, $F_{1,47} = 30.2$, $p < 0.001$; Fig. 3). The percentage of individuals that needed liberation from other saplings and lianas decreased over time in the tending

treatment and increased in the planting + tending treatment (Repeated measures ANOVA, for time x treatment, $F_{4;180} = 22.5$, $p < 0.001$; Fig. 3). The number of liberation events in six assessments (from month 6 to month 48) was higher in planting (2.82 times ± 0.04 SE) than in tending (1.67 ± 0.07 SE) (ANOVA, $F_{1;1456} = 183.9$, $p < 0.001$).

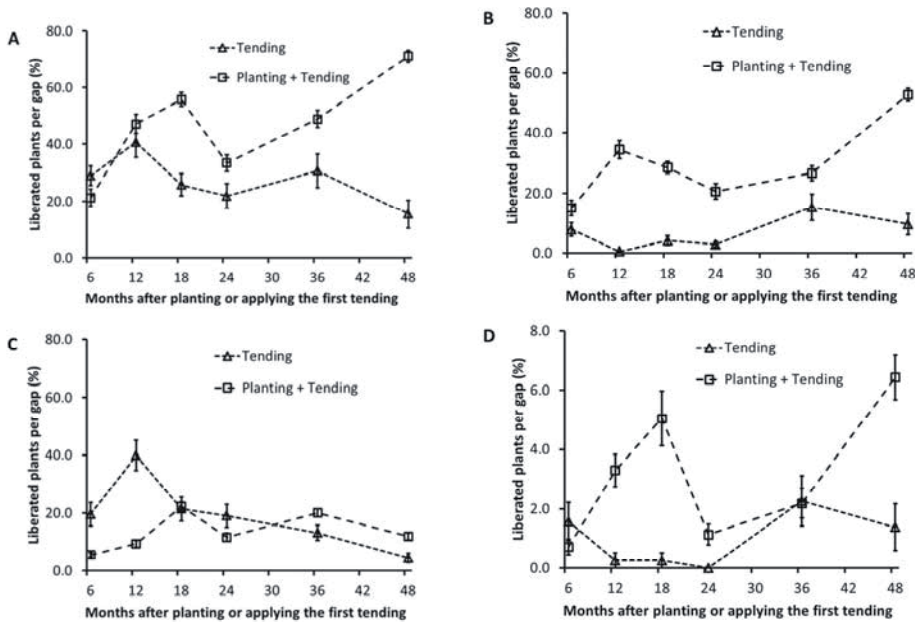


Fig. 3. Percentage (\pm SE) of plants liberated through time (A), to reduce competition from overshadowing plants (B), lianas (C), or both (D) in two treatments (tending and planting + tending) in the managed forests of Orsa Florestal, Jari Valley, Brazil. Note that 'y' axis is not the same.

Discussion

Logging gaps and sampled species

In our experiment logging gaps were larger than gaps described by Lopes et al. (2008) in Southern Amazon or by Doucet et al. (2009) in Central Africa. The logging gaps in Jari have approximately the same size of those reported by Park et al. (2005) in Bolivia, with an average of 395 m^2 (range: 108 to 1246 m^2). Large gaps in Jari are mainly due to the large crowns of the harvested species *D. excelsa* and *C. villosum*. In the logging gaps in which natural regeneration was sampled, we found a total of 50 commercial tree species (average of 8.57 ± 0.48 SE commercial species per gap), of which only 10 (37%) are commercial species currently being harvested and traded by Orsa Florestal in Jari Valley. In a similar study carried out in the logging compartment harvested in 2008, it was found that 41% of the traded

species by Orsa were present in the logging gaps sampled (Falkowski, 2011). Considering our work and Falkowski (2011), the total number of species found was 15, or 56% of the 27 species traded by Orsa. These results suggest that there may be a lack of regeneration of commercial species in the area, indicating that some commercial species are occurring in small numbers or even are absent in the managed forest investigated along this study. This shortage of seedlings of commercial species in logging gaps would justify the application of silvicultural treatments aiming to artificially increase their density, such as enrichment planting (D'Oliveira, 2000a; Lopes et al., 2008; Keefe et al., 2009). Sufficient natural regeneration of commercial valuable species is a crucial step to reach sustainable harvesting cutting cycles. The lack of regeneration of desirable species in managed forests is a problem that has also been reported in the Western Brazilian Amazon (D'Oliveira, 2000a) and in Bolivia, especially for light demanding species (Mostacedo and Fredericksen, 1999; van Rheenen et al., 2004; Park et al., 2005).

Mortality and growth rates

Mortality rates of the tending and control treatments remained approximately the same over the 18 first months (Fig. 1). After that, mortality accelerated in the control treatment, probably because individuals were overshadowed or outcompeted by taller trees. The planting + tending treatment had the highest mortality rates over all measurements (Fig. 1). The stress caused by transferring the seedlings from the nursery to the logging gaps, and by the fact that seedlings did not received any additional treatment might have contributed to the highest mortality rates (when compared to the other treatments) observed during the first 12 months. Another possible reason is the quality of the seedlings that may interfere in their survival rates (D'Oliveira, 2000a). All planted seedlings were produced from seeds collected in the management area of Orsa, but without a strict control on their production. The mortality rates in the two first assessments (12 months), however, were not higher than the mortality rates found in another enrichment planting experiment in the eastern Amazon (Gomes et al., 2010). Differences in initial mortality rates among the treatments could also be due to the fact that many naturally established individuals were older than the planted ones, having lower mortality rates. Finally, the increase in mortality rates of the planting + tending over time was due to few species. At the last measurement *P. filipes* showed a survival rate of only 35.5%, followed by *B. guianensis* with a survival rate equal to 66.4%. The other species had an average survival rate of 78.1%, not much lower than the average of the other treatments (G. Schwartz, unpublished data).

Tending was the most effective treatment for obtaining higher growth rates of saplings (Table 1, Fig. 2), except in the case of the single most dominant individual (Fig. 2). This result indicates that even co-dominant individuals require some tending to achieve higher growth rates. Our results also show that the mechanical control of competition is an efficient method for increasing growth rates (cf. Pariona et al., 2003). One more aspect in favour of tending is that it demanded less effort for liberating seedlings and saplings than planting + tending. This difference is probably due to the fact that plants growing in the tending treatment needed to be liberated less from overshadowing plants and lianas (Fig. 3 B and C) than plants growing in the planting + tending treatment. One probable cause for this difference in liberation effort is that in the planting + tending treatment all previous vegetation was slashed down, which opened the gap area sufficiently to create conditions for germination of pioneers (Fox, 1976). The problem of pioneer infestation might have been reduced if gaps used for planting were newer (maximum one year), so the planted seedlings would have more chances to compete with the regeneration (pioneers and non-commercial species), demanding less liberation events (Pariona et al., 2003; Ohlson-Kiehn et al., 2006; Navarro-Cerillo et al., 2011). Besides, newer gaps, with less established regeneration, would also demand less costs to be prepared for planting. Positive effects on growth rates of regeneration in logging gaps due to the silvicultural treatments application are also reported in Indonesian (Kuusipalo et al., 1996) and Amazonian forests (D'Oliveira, 2000a; Lopes et al. 2008; Keefe et al., 2009).

The response of species belonging to a given functional group to the different treatments was not homogenous. In the case of the LLP, some species grew better in the treatment with liberation (*G. glabra* and *L. procera*), while others did not show that response (*J. copaia* and *Jacaranda* sp.). A similar situation was observed in the case of the PST *D. excelsa* and *Trattinnickia* sp. that grew more than *B. parinarioides*, *H. balsamifera*, *Q. albiflora*, and *T. myrmecophila*. Hence, tending should be more specifically applied to those more responsive species. Like in tending, the most responsive species in growth should be preferred in plantations (Tonini et al., 2008). Long term assessments in our experiment, however, would better show the performance of slow grow species (Schulze et al., 2008a; Reis et al., 2010) in logging gaps.

When to apply tending or planting + tending treatments?

The treatment of planting + tending presents some disadvantages when compared to the tending treatment. Firstly, enrichment planting implies more work (e.g. seedling production and gap preparation) being consequently more costly (Schulze, 2008; Bais, 2012)

than identification and liberation of commercial seedlings/saplings naturally growing in logging gaps. Secondly, planted individuals presented higher mortality rates (Fig. 1) and lower growth rates (Fig. 2) than naturally established seedlings and saplings, even when initial height differences were corrected. Finally, a larger proportion of plants growing in the planting + tending gaps had to be liberated (Fig. 3) with a higher frequency than plants in the tending treatment as they had proportionally more plants being overshadowed by other plants or having liana infestation.

In our experiment, tending naturally established seedlings/ saplings in logging gaps showed to be more efficient in terms of growth and mortality than planting + tending. We suggest, however, that this technique should only be applied in managed areas where natural regeneration of commercial species is sufficiently available. On the other hand, if commercial species are absent or in very low numbers, enrichment planting becomes the best alternative, since it will allow adding highly valuable species to the logging gaps (Lamprecht, 1989). Given that this treatment is more costly, it would be desirable to plant highly valuable species to cover extra costs with of preparing gaps, producing, planting seedlings and the need of more often liberation events.

Conclusions

Tending naturally established seedlings and saplings in logging gaps is more efficient in terms of growth, mortality, and frequency of application of liberation events than the treatment of enrichment planting + tending seedlings. This later treatment should be chosen, however, when there is not sufficient natural regeneration of commercial species. Planted species should have high initial growth rates to diminish maintenance costs and high commercial values to cover costs made and increase future income. We also suggest the application of both treatments within the same management area, tending available regeneration wherever possible, and planting species that are adapted to local conditions whenever needed. We believe that our results are relevant for the Amazon, as well as other tropical forests worldwide, given that is relevant for solving the problem of natural regeneration shortage after logging, which may prevent new cutting cycles.

Profitability of post-harvesting silvicultural treatments applied in
logging gaps in the Brazilian Amazon

**Gustavo Schwartz, Anna Liza S. Bais, Marielos Peña-Claros, Marjanke A. Hoogstra-
Klein, Godefridus M. J. Mohren, Bas J. M. Arts**

(Submitted for publication)



Forest management area of Orsa Florestal – Brazil

Abstract

Forest management in the Brazilian Amazon follows a polycyclic silvicultural system (PSS) where only selected species and individuals with a minimum diameter cutting (≥ 45 cm in dbh) are harvested. Many studies show, however, that managed tropical forests have problems of regeneration and the harvested species will decrease timber yields. In this study it was analysed the profitability of two post-harvesting silvicultural treatments: tending the naturally established regeneration and enrichment planting, both applied in logging gaps for promoting the regeneration of commercial species. Their profitability was compared with the current practice where logging gaps are abandoned after harvesting. The field experiment was carried out and monitored in terms of growth rates during four years, in the management area of the forestry company Orsa Florestal in Jari Valley, eastern Amazon, Brazil. The results were projected into the future to simulate timber production (round- and sawnwood). Future scenarios were tested through a sensitivity analysis, which included changes in the interest rates, timber prices, and harvesting costs. Although having higher benefits, both tending and enrichment planting were not profitable under the interest rate of 6% and timber prices at the domestic market in Brazil. The sensitivity analysis showed that only sawnwood produced through tending under an increase in timber prices of 750% would make the treatment profitable. Profitability would be possible by reducing costs in establishment and maintenance of the managed logging gaps, while higher benefits would come by favouring more valuable and fast-growing species.

Once these treatments become more profitable than the current practices, forest management would be a more economically competitive land use in the Amazon.

Key words: Polycyclic silvicultural system; Jari; cost-benefit analysis; enrichment planting; regeneration; tending

Introduction

Forestry companies, including the certified ones, in the Brazilian Amazon apply forest management following a polycyclic silvicultural system (PSS), where only the selected trees are harvested and the remaining ones may contribute to future cutting cycles (Matthews, 1989; Silva, 1997; Dawkins and Philip, 1998; D'Oliveira, 2000b). In the PSS applied in Brazil the cutting cycles are expected to last 30 years and the harvested trees must have a minimum diameter cutting (MDC) of 45 cm in dbh (diameter at breast height – 1.30 m). According to the Brazilian environmental regulations for forest management in the Amazon, shorter cutting cycles are permitted when the timber volumes harvested are low as they allow faster recovery of the forest (MMA, 2006). The main objective of the PSS applied in the Brazilian Amazon is to harvest timber under continuous cutting cycles, while the ecosystem processes and services are maintained in good conditions.

The PSS applied in the Brazilian Amazon has improved remarkably over the past three decades, especially through the adoption of reduced-impact logging (RIL) techniques. RIL has been introduced to improve the efficiency in harvesting operations through careful and detailed operations, while unnecessary damage on the remaining trees is avoided, diminishing chances of forest degradation, and increasing possibilities of higher yields in future harvestings (Putz et al., 2008). RIL is more environmentally friendly than conventional logging (CL), having less destructive effects on the animal and plant communities (Azevedo-Ramos et al., 2006; Sebbenn et al., 2008; Imai et al., 2009). RIL techniques may even improve post-harvesting survival rates of standing trees (Johns et al., 1996; Pereira et al., 2002), increasing chances of these individuals being available in next cutting cycles (Zarin et al., 2007; Macpherson et al., 2012). Despite of these advantages, RIL requires higher investments than CL (Medjibe and Putz, 2012), so that it only becomes more profitable in the long-term. RIL also increases the possibilities of a company to be certified and to have access to more profitable markets (Barreto et al., 1998; Boltz et al., 2001; Holmes et al., 2002).

There are still no examples of a second cutting cycle (30 years) made in Brazil under the PSS. Long-term simulations of future timber yields suggest that future harvestings of the same commercial species and using a 30 year cutting cycle will not provide the same timber volume obtained in the first cutting cycle (Dauber et al. 2005; Azevedo, 2006; Sist and Ferreira, 2007; Valle et al., 2007). One reason for these results may be related to the low regeneration rates of commercial species. Several studies have found that managed tropical forests may not have enough regeneration of commercial species as it is reported in the

Western Amazon (D'Oliveira, 2000a), Bolivia (Mostacedo and Fredericksen, 1999; Van Rheenen et al., 2004; Park et al., 2005), and in Central Africa (Doucet et al., 2009).

According to the current forest management regulations in Brazil, no post-harvesting interventions are expected in logging gaps (MMA, 2006) assuming that managed forests will regenerate by themselves. The regeneration, however, depends on the forest conditions after logging (Fredericksen and Putz, 2003; Sist and Brown, 2004). Hence, the Brazilian forest management regulations require that 10% of the harvested species (or at least three adults per 100 ha) are left behind. Logging is not allowed for species with less than three adults per 100 ha (MMA, 2006). These legal procedures are very important but possibly not enough for ensuring sufficient regeneration of the currently harvested commercial species in the Eastern Amazon (Falkowsky, 2011; Schwartz et al. – unpublished data).

Especially because of the present problems with regeneration and the high uncertainties on future timber yields, several studies suggest the application of post-harvesting silvicultural treatments aimed to ensure enough regeneration for future harvesting cycles (Fredericksen and Pariona, 2002; Dauber et al., 2005; Schwartz et al., 2012; Soriano et al., 2012). Among these post-harvesting silvicultural treatments, tending through liberation from competitors and lianas and enrichment planting in gaps created by logging are some feasible silvicultural alternatives (Lopes et al., 2008; Doucet et al., 2009). Like RIL, however, these treatments require high long-term financial investments, which may become a hurdle to adopt them in forest management (Schulze, 2008; Keefe et al., 2009).

This study compares the profitability of two post-harvesting silvicultural treatments (tending and enrichment planting) to the current standard RIL practices where logging gaps are abandoned without any silvicultural treatment. Moreover, it was compared the long-term profitability of the three practices over scenarios differing in (a) interest rates, (b) timber prices and (c) harvesting costs. The paper is organized in the following way: firstly it is provided some background information on the experimental post-harvesting silvicultural treatments applied in gaps created by RIL and, secondly, it is described the methods applied to do growth rate projections, profitability calculations, and a sensitivity analysis. Thirdly, the results are presented and discussed, considering their implications in future investment decisions on the application of tending and enrichment planting in logging gaps. Finally, the possible consequences of these silvicultural treatments on forest management in the Amazon and other tropical forests are discussed.

Post-harvesting silvicultural treatments experimentally applied in logging gaps: future projections

The experiment used in this study was established in the forest management area of Orsa Florestal S.A. under the project “Gaps Management” (coordinated by Orsa Florestal and Embrapa Eastern Amazon). The forest management area of Orsa Florestal is located at Jari Valley, municipality of Almeirim (01°09'S and 52°38'W), Pará state, Brazil. Orsa Florestal manages natural forests for timber and non-timber production and since 2003 the company has been applying RIL in its harvesting operations. The company currently sells timber certified under the scheme of the Forest Stewardship Council (FSC) to the domestic and international markets. The total area managed by the company is 545,000 ha, of which 92 thousand are fully protected areas (Orsa Florestal, 2012). The experiment consisted of three treatments established between March and September 2006 in gaps created by RIL in 2004. In one treatment the marked individuals were only monitored, they had no additional silvicultural treatments, following the current forest management regulations. This treatment is referred as “standard RIL” hereafter. In the second treatment, tending was applied (liberation against other competing plants and lianas) to marked seedlings and saplings of commercial species naturally established in the gaps. In the last treatment enrichment planting in logging gaps using commercial species was applied. Silvicultural treatments and growth measurements were taken twice per year from 2006 to 2008 and once per year from 2009 to 2010 (Schwartz et al., in review).

The future timber yield at the end of the third and fourth cutting cycles (years 60 and 90) was projected by simulating long-term growth of the most dominant individual(s) in each gap. The number of trees allowed to become mature varied with gap size: one adult tree per gap $\leq 455 \text{ m}^2$, two in gaps between 455 to 680 m^2 , and three in gaps $> 680 \text{ m}^2$. Long-term growth projections were based on: a) the observed growth rate in the first four years of the experiment (applied until the time the dominant individuals attain 10 cm in dbh) and b) the average annual diameter increment of adult and sub-adult commercial tree species ($\geq 10 \text{ cm}$ in dbh). The latter data were obtained from literature (Condit et al., 1993; Silva et al., 1996; Alder and Silva, 2000; Schulze, 2003; Phillips et al., 2004; Azevedo et al., 2008; Schulze et al., 2008a; Sebbenn, et al., 2008) and datasets of Embrapa Eastern Amazon (Table 1). It is assumed that the dominant individual(s) in each gap will remain alive and will attain commercial sizes, so that mortality rates were not included in the projections. Individuals that reach the commercial size ($\geq 45 \text{ cm}$ in dbh) in the year 60 or 90 have the projected diameter

converted into volume estimates, according to the diameter-based volume equation developed by Silva et al. (1985) for the Tapajos National Forest in the Eastern Amazon:

$$\text{Volume} = e^{-7.62812 + 2.1809 \cdot \ln(\text{dbh})}$$

The estimated volume of timber or roundwood was then converted into sawnwood volume by multiplying the estimated roundwood yield by 42%, which is the average processing efficiency in the Amazon region (Lentini et al., 2005).

Table 1

Species with dominant individuals in logging gaps differing in silvicultural treatment received. The number of individuals per treatment, the average (range) growth rates of (sub) adult trees, and the market prices for roundwood (RW) and sawnwood (SW) are also provided.

Species	Standard d RIL	Tending g	Enrichment ent planting	Growth rates ^a (cm year ⁻¹)	RW ^b (US\$ m ⁻³)	SW ^b (US\$ m ⁻³)
<i>Anacardium giganteum</i>	-	-	12	0.48 (0.43-0.54)	61	297
<i>Bagassa guianensis</i>	-	-	26	0.47 (0.35-0.59)	85	401
<i>Bombacopsis nervosa</i>	1	-	-	0.64 (0.64)	61	210
<i>Carapa guianensis</i>	-	-	10	0.45 (0.29-0.60)	90	422
<i>Dinizia excelsa</i>	2	-	-	0.45 (0.36-0.53)	100	452
<i>Jacaranda copaia</i>	1	-	-	0.66 (0.38-0.92)	110	422
<i>Jacaranda</i> sp.	1	-	-	0.54 (0.54)	118	422
<i>Laetia procera</i>	10	16	-	0.42 (0.22-0.71)	69	326
<i>Parkia reticulata</i>	1	-	-	0.73 (0.62-0.93)	50	111
<i>Qualea albiflora</i>	-	1	-	0.70 (0.63-0.76)	76	326
<i>Schefflera morototoni</i>	-	1	-	0.76 (0.54-0.97)	73	326
<i>Tachigali myrmecophila</i>	3	3	-	1.16 (0.94-1.41)	72	315
<i>Tapirira guianensis</i>	-	2	-	0.66 (0.62-0.68)	69	326
<i>Vochysia vismifolia</i>	-	1	-	0.72 (0.64-0.81)	78	336

^a SEMA (2012) and Pereira et al. (2010); ^b Condit et al. (1993), Silva et al. (1996), Alder and Silva (2000), Phillips et al. (2004), Schulze (2003), Azevedo et al. (2008), Schulze et al. (2008), Sebbenn, et al. (2008), and EMBRAPA datasets.

Methods

Net Present Value (NPV)

To estimate the profitability of the long term investments, it was used the Net Present Value (NPV). The NPV is a very common economic figure used to present forest

profitability using discounted cash flow analysis. The NPV is calculated by adding all the discounted benefits and cost over each harvesting or cutting cycle:

$$NPV = \sum_{t=0}^n \left(\frac{B_t}{(1+r)^t} - \frac{C_t}{(1+r)^t} \right)$$

where B_t is the revenue in year t , C_t is the cost in year t , r is the discount rate per year (in percentage), t is the year when revenue or cost occurs, and n is the time for having revenues, in this case each cutting cycle (in years).

If the outcome of the NPV for a given forest is zero or negative, then the cost over the cutting cycle equal to or greater than the benefits. This means that at the chosen discount rate, the investment is not profitable. If the outcome of the NPV is larger than zero, then the investment is expected to be profitable. The NPV can also be used to compare several alternatives and choose the alternative with the highest net return; this however requires that all alternatives considered have the same length of time.

Discount rate

Choosing the appropriate discount rate is crucial for determining the NPV of an investment, especially the power of discounting in relation to benefits or cost which occurs in the far future can be excessive. It is therefore not surprising that the issue of choosing the “right” discount rate to calculate the NPV for forest investments is a long-standing, and still continuing, debate (Livingstone and Tribe, 1995).

One practical way to choose the discount rate is to determine the opportunity cost of the capital needed for an investment, i.e. the rate which the capital needed for the forestry investment might return if it would have been invested in an alternative (Row et al., 1981). Based on this approach, it was used the discount rate on the long-term interest rate used by the National Development Bank (BNDES) of Brazil, currently at 6% per year. This bank enables long-term financing for projects of micro, small, medium and large enterprises, focusing on industry, infrastructure, agriculture, trade and services. In the sensitivity analysis we will use other rates as well, i.e. 3% and 9%.

Cost and benefits

Future benefits were calculated taking into account the growth and timber yields simulations of each of the dominant individuals per gap. A given tree would be harvested when attaining the minimum diameter cutting (MDC) of 45 cm either in year 60 or 90. Then the benefits were calculated by multiplying the estimated timber volume (m^3) of round- and sawnwood by their prices in the domestic market and subtracting the cost of harvesting, transport, and processing. The mean timber prices (round- and sawnwood) per m^3 were obtained from SEMA (2012) and Pereira et al. (2010) (Table 1), and the costs of harvesting and wood processing from Pereira et al. (2010) and Orsa Florestal. The net benefits per hectare (NPV ha^{-1}) were calculated for round- and sawnwood produced by each one of the treatments at years 60 and 90.

The costs on harvesting, transport, and processing were assumed to be constant overtime. For calculating the establishment and maintenance costs per gap of each treatment, the following costs were considered: seedling production, gap selection and mapping, seedlings selection, gap preparation, and seedlings transport and transplanting, labour, and transport of workers (Table 2). The transport costs (the distance from the base to the management unit was 12 km) were based on the costs of renting a truck, pick-up, and car, including their fuel consumption: truck 0.22 l km^{-1} (diesel), pick-up 0.13 l km^{-1} (diesel), and car 0.10 l km^{-1} (petrol). Petrol was also used for the chainsaw (needed to clean some gaps used for enrichment planting), consuming 0.70 l h^{-1} . Equipment costs included a shovel (1pc), hole diggers (2 pcs), and machetes (3 pcs). Regarding the maintenance costs, labour was estimated based on the time required for liberating plants in each gap and maintenance (Table 2). The average establishment and maintenance costs per treatment were calculated per gap and per hectare, using an average of $3.44 \text{ logging gaps ha}^{-1}$ (Orsa Florestal, unpublished data).

Table 2

Average establishment and maintenance costs (US\$) per gap and per hectare over four years for tending (Ten) and enrichment planting (En Pl) in logging gaps in Jari Valley, Pará, Brazil. The standard RIL treatment had the total establishment and maintenance costs equal to zero, since no silvicultural interventions were applied.

Activity	Average cost per gap		Average cost per hectare	
	Ten	En Pl	Ten	En Pl
Seedling production	0.00	35.89	0.00	123.46
Gap selection	0.48	0.48	1.65	1.65
Personnel	0.29	0.29	1.00	1.00
Transport	0.19	0.19	0.65	0.65
Gap mapping	2.10	2.10	7.22	7.22
Personnel	1.10	1.10	3.78	3.78
Transport	1.00	1.00	3.44	3.44
Seedlings selection	2.68	0.00	9.22	0.00
Personnel	1.59	0.00	5.47	0.00
Transport	1.09	0.00	3.75	0.00
Gap preparation	0.00	13.04	0.00	44.86
Personnel	0.00	6.15	0.00	21.16
Transport	0.00	5.42	0.00	18.64
Equipment	0.00	1.47	0.00	5.06
Seedlings transport and transplanting	0.00	22.62	0.00	77.81
Personnel	0.00	7.17	0.00	24.66
Transport	0.00	15.45	0.00	53.15
Total establishment cost	5.26	74.13	18.09	255.00
Maintenance cost at year 1	10.46	10.46	35.98	35.98
Maintenance cost at year 2	12.03	12.03	41.38	41.38
Maintenance cost at year 3	13.24	13.24	45.55	45.55
Maintenance cost at year 4	6.53	6.53	22.46	22.46
Total establishment and maintenance costs	47.52	116.39	163.46	400.37

Sensitivity analysis

A sensitivity analysis was made to evaluate the profitability of producing round- and sawnwood through each one of the post-harvesting silvicultural treatments (standard RIL, tending, and enrichment planting) under different scenarios. The scenarios differed in: a) interest rates, b) timber prices, and c) timber prices with harvesting costs. Besides of calculating NPV ha⁻¹ an interest rate of 6%, the estimates of NPV were done with a lower (3%) and a higher (9%) interest rate. Considering that the average price of roundwood in 1989 was US\$ 32 m⁻³ (Verissimo et al., 1992) and in 2009 US\$ 111 m⁻³ (Pereira et al., 2010),

the price increased approximately 250% in 20 years. Based on this, the NPV ha⁻¹ of the round- and sawnwood produced per treatment was calculated considering different scenarios for timber prices increase (250% every 20 years). Given that harvesting costs were US\$ 12 m⁻³ in 1989 and US\$ 31 m⁻³ in 2009 (Verissimo et al., 1992; Pereira et al., 2010), there was an increase of 150% in 20 years. Consequently, the NPV ha⁻¹ of the round- and sawnwood per treatment was calculated taking into account both prices increase (250% every 20 years) and harvesting costs increase (150% every 20 years).

Results

The application of post-harvesting silvicultural treatments in logging gaps resulted in higher benefits than in the standard RIL. Tending showed the highest benefits projected for round- and sawnwood produced at year 60, while enrichment planting had the highest benefits projected for both kinds of wood produced at year 90 (Table 3). But these higher benefits did not result in positive NPVs. All NPVs for round- and sawnwood produced by tending and enrichment planting at years 60 and 90 were lower than zero (Table 4), considering the interest rate of 6% used in this research. Only the NPVs for round- and sawnwood produced by the standard RIL were positive. This suggests that no investments on post-harvesting silvicultural treatments in logging gaps should be done as this needs higher returns to cover the extra cost of these post-harvesting treatments.

Table 3

Average projected benefits (US\$ ha⁻¹) per kind of wood produced in each harvesting year (60 = 3rd harvesting cycle and 90 = 4th harvesting cycle) over three silvicultural treatments (standard RIL, tending, and enrichment planting) in logging gaps in Jari Valley, Pará, Brazil.

Kind of wood	Harvesting year	Standard RIL	Tending	Enrichment planting
Roundwood	60	83.45	151.37	3.93
Sawnwood	60	341.43	630.02	26.77
Roundwood	90	262.17	212.58	281.97
Sawnwood	90	932.71	1018.63	1333.21

Table 4

Net Present Value (US\$ ha⁻¹) of roundwood (RW) and sawnwood (SW) produced under three silvicultural treatments (standard RIL, tending, and enrichment planting) using different long-term interest rates, increases in timber prices, and increases in timber prices with harvesting costs. Trees are harvested when attaining ≥ 45 cm in diameter.

Long-term interest rates

Interest rate	60 years			90 years		
	3%	6%	9%	3%	6%	9%
Standard RIL (RW)	14.16	2.53	0.47	18.33	1.38	0.11
Standard RIL (SW)	57.95	10.35	1.94	65.22	4.92	0.40
Tending (RW)	-132.04	-147.92	-146.86	-142.87	-151.38	-147.62
Tending (SW)	-50.80	-133.41	-144.14	-86.50	-147.13	-147.28
Enrichment planting (RW)	-393.98	-389.30	-384.60	-374.93	-387.93	-384.50
Enrichment planting (SW)	-390.10	-388.60	-384.47	-301.42	-382.38	-384.05

Increases in timber prices

Increase in timber prices	60 years			90 years			
	250%	500%	750%	250%	500%	750%	1125%
Standard RIL (RW)	22.10	41.67	61.24	10.92	20.45	29.98	44.28
Standard RIL (SW)	46.31	82.27	118.22	21.85	38.78	55.71	81.11
Tending (RW)	-112.63	-77.34	-42.05	-142.02	-132.65	-123.28	-109.23
Tending (SW)	-67.53	-1.65	64.22	-128.69	-110.26	-91.82	-64.17
Enrichment planting (RW)	-388.25	-387.20	-386.14	-377.18	-366.44	-355.69	-339.58
Enrichment planting (SW)	-386.00	-383.40	-380.80	-359.44	-336.50	-313.56	-279.16

Increases in timber prices with harvesting costs

Increase in timber prices	60 years			90 years			
	250%	500%	750%	250%	500%	750%	1125%
Increase in costs	150%	300%	450%	150%	300%	450%	675%
Standard RIL (RW)	14.15	25.77	37.40	7.27	13.16	19.05	27.88
Standard RIL (SW)	40.26	70.17	100.08	19.08	33.24	47.39	68.63
Tending (RW)	-126.92	-105.92	-84.92	-145.95	-140.52	-135.09	-126.95
Tending (SW)	-78.41	-23.41	31.59	-131.69	-116.25	-100.81	-77.65
Enrichment planting (RW)	-388.70	-388.10	-387.50	-381.40	-374.87	-368.34	-358.54
Enrichment planting (SW)	-386.35	-384.09	-381.83	-362.65	-342.92	-323.19	-293.59

The standard RIL had no costs for establishment and maintenance, since silvicultural interventions (investments) are not required. The establishment costs for enrichment planting were 14 times higher than for tending due to the costs of seedling production, gap preparation, transport, and transplanting. The maintenance costs were the same for both treatments, representing 89% of the total costs of tending and 36% of enrichment planting (Table 2). Based on the growth projections, no individuals attained the MDC at year 30 (2nd cutting cycle).

Table 4 shows the consequences of different scenarios with lower or higher interest rates, different timber prices, and different combinations of timber prices and harvesting costs. The treatments of tending and enrichment planting showed negative NPVs for both 3% and 9% interest rate scenarios. Not surprisingly, the higher interest rate results in negative NPVs for the treatment scenarios, but it is still profitable for the standard RIL.

Tending showed positive NPVs only in two scenarios: timber prices increase of 750% and timber prices increase of 750% with harvesting costs increase of 450% for sawnwood at year 60 (Table 4). But both positive NPVs of tending were lower than the NPVs showed by the standard RIL. The other scenarios for round- or sawnwood produced by tending or enrichment planting at year 60 and all tested scenarios at year 90 had negative NPVs.

Discussion

Profitability

The higher benefits showed by tending and enrichment planting when compared to the standard RIL are an indication of the efficiency of these post-harvesting silvicultural treatments (Pariona et al., 2003; Lopes et al., 2008; Schwartz et al., in review). Although the highest benefits showed by the treatment of tending at year 60 and by enrichment planting at year 90 (Table 3), they are not profitable under the interest rate of 6% and the current timber prices in the domestic market. According to the sensitivity analysis, positive revenues would only be possible when producing sawnwood through tending at year 60 and if timber prices increase 750% (Table 4). Even if timber prices maintain an increase of 250% each 20 years (Pereira et al., 2010), which is expressed in positive NPVs, sawnwood produced by tending would be lesser profitable than sawnwood produced by the standard RIL at the year 60 (Table 4). Therefore, the standard RIL would still be better in terms of investment than tending or enrichment planting. This treatment is even profitable under a higher interest rate (9%), suggesting that the available regeneration in logging gaps may produce profitable harvestings.

The uncertainties related to the profitability of post-harvesting silvicultural treatments assessed in this study are due to timber prices, harvesting, and processing costs. Moreover, the establishment and maintenance cost of the managed logging gaps. Each of these parameters can strongly make investments profitable or not, with timber prices having the largest potential to increase financial returns. Some of these variables may be changed through improved management techniques for achieving a higher profitability. In the case of the studied treatments, a higher profitability would imply in lower costs of establishment and maintenance of the managed logging gaps and in higher benefits of the treatments. In the following sections these two options will be discussed in more detail.

Reducing cost

Lower costs would be possible under a better understanding and improvement of the tending and planting techniques applied in logging gaps (Pariona et al., 2003; Schulze, 2008; Keefe et al., 2009). The costs of enrichment planting in this study were similar to US\$ 378.00 ha⁻¹ recorded by Lopes et al. (2008) in southern Amazon but much higher than the US\$ 22.80 ha⁻¹ in Cameroon (Doucet et al., 2009) or the US\$ 40.00 ha⁻¹ reported in Fazenda Cauaxi, eastern Amazon (Schulze, 2008). Most of the costs for enrichment planting are on seedling production (US\$ 123.46 ha⁻¹) during the establishment period (Table 2). In this study the total costs of establishment and maintenance varied from US\$ 163.46 ha⁻¹ in tending to US\$ 400.37 ha⁻¹ in enrichment planting (Table 2). Given that, the establishment costs of the treatments were based on an experimental design, it is expected that costs may decrease when applied in a larger or commercial scale. For enrichment planting the cost on seedlings production may decrease if forestry companies might maintain their own nursery in their management areas.

Planting costs could be reduced substantially by direct sowing of seeds (Van Rheenen et al., 2004) instead of producing and planting seedlings. This procedure would strongly reduce costs of seedlings production and transport followed by transplanting, the two highest establishment costs for enrichment planting (Table 2). Another option is to use a larger spacing among plants. The spacing used in this study (2.5 x 2.5 m) was larger than the 4 x 4 m used in Fazenda Cauaxi by Schulze (2008) or 2 x 4 m used in Central Africa by Doucet et al. (2009) which demanded fewer seedlings and, consequently, presented lesser establishment costs. Maintenance costs could also be reduced, instead of applying liberation twice a year, a single annual liberation of competing individuals along the first four years could be enough. This frequency of liberation might be sufficient to improve growth and survival rates in both

tending and enrichment planting as observed in other studies (Schulze, 2008; Doucet et al., 2009). If these two silvicultural measurements would be taken (i.e. spacing of 4 x 4 m with a yearly maintenance applied during the first four years), costs would be reduced from the current US\$ 400.37 to nearly US\$ 220.00 ha⁻¹ in the enrichment planting treatment. Similarly, costs on maintenance of the tending treatment could also be lowered by increasing the interval between the liberation events, without losing efficacy of the method. Costs might be decreased from US\$ 163.46 to approximately US\$ 100.00 ha⁻¹ by reducing liberation events from twice to once a year. Therefore the costs of liberation per gap would be nearly the same of those reported by Pariona et al. (2003) in Bolivia. Moreover, the costs involved gap preparation in enrichment planting would be lower if newer logging gaps were used, reducing cost on gap preparation (Table 2). It was used 2-years logging gaps, which demanded a longer time for preparation due to the advanced regeneration. In an enrichment planting experiment carried out in the Jari Valley, where 1-year logging gaps were used, the preparation time was remarkably shorter (G. Schwartz, unpublished data).

Increasing benefits

The benefits of applying tending and enrichment planting in logging gaps could be increased by favouring the most valuable and fast-growing species (Tonini et al., 2008; Gomes et al., 2010). The most valuable species in this study were *Tabebuia serratifolia*, *Hymenaea courbaril*, and *Dinizia excelsa*. These three species were planted, but they did not reach dominant positions by the last measurement (four years after the treatment application). An option to increase benefits would be to cut or girdle other dominant individuals (even the commercial ones) to favor individuals belonging to a more valuable species (Pariona et al., 2003; Wadsworth and Zweede, 2006). Many gaps receiving the enrichment planting treatment had *Anacardium giganteum* as the most dominant individual, decreasing chances of *T. serratifolia*, *H. courbaril*, and *D. excelsa* (all more expensive than *A. giganteum*) to take the most dominant position. For the tending treatment, cutting or girdling the most dominant individuals of *Laetia procera* or *Tachigali myrmecophila* could give dominance to individuals of *Jacaranda* sp. and *Dinizia excelsa*, both highly valuable.

Despite the fact that tending and enrichment planting showed to be not profitable treatments when compared to the standard RIL, they may be an important tool for conserving rare and highly valuable species (Grogan et al., 2008; Lopes et al., 2008; Schulze et al., 2008a; Schulze et al., 2008b; Keefe et al., 2009; Reis et al., 2010). Therefore, in the long run, the treatments may bring additional ecological and economic value to the forest, which the

profitability analysis used in this paper cannot account for. Thus, they may increase the competitiveness of forest management in relation to other land uses in the Amazon in the future, but it would require additional investments today, which the market cannot bring. Here the role of governments, donors or private funds to invest in “unprofitable” silvicultural treatments is crucial (Boltz et al., 2001; Bacha and Rodriguez, 2007; Keefe et al., 2012).

Conclusions

The post-harvesting silvicultural treatments of tending the naturally established regeneration and enrichment planting in logging gaps bring more benefits than the standard RIL. But they are not profitable under the interest rate of 6% and the current timber prices in the Brazilian domestic market. The standard RIL is profitable even under an interest rate of 9%. The main cost for tending was maintenance, while seedling production, transport, and transplanting were the main costs for enrichment planting. According to the sensitivity analysis, only sawnwood produced by tending under an increase of 750% in timber prices at year 60 (3rd cutting cycle) would be profitable, but still lesser than the standard RIL. Thus, these two treatments should, from an economic perspective, not be invested, although they may be an important tool for conserving rare and highly valuable tree species in the Amazon.

Chapter 6

Synthesis



Forest management area of Orsa Florestal – Brazil

Introduction

Several studies show that managed tropical forests may not have enough regeneration of commercial species and that the harvested commercial species may have lower timber yields in future cutting cycles (Mostacedo and Fredericksen, 1999; Sist and Ferreira, 2007; Valle et al., 2007; Putz et al., 2008; Peña-Claros et al., 2008b). A possible alternative to mitigate the problem is the improvement of the regeneration of commercial species (Pariona et al., 2003; Park et al., 2005; Lopes et al., 2008; Schulze, 2008; Doucet et al., 2009; Keefe et al., 2009). Tending naturally established regeneration by diminishing competition with non-commercial species and lianas, and enrichment planting in gaps created by logging are feasible possibilities. These treatments, however, require long-term financial investments, which invokes uncertainty on their profitability (Keefe et al., 2009; Keefe et al., 2012).

The general objective of the research done for this PhD thesis was to study the regeneration ecology of commercial species in order to identify the silvicultural treatments that would help achieve a move towards ecologically and economically sustainable forested land uses. Four specific research questions were addressed:

- 1) How does the regeneration of commercial tree species respond to the different levels of disturbance created by reduced-impact logging (RIL)?
- 2) How does the regeneration of commercial tree species respond in the medium term to disturbance caused by RIL?
- 3) Which of the two post-harvesting silvicultural treatments applied in logging gaps is the most suitable: tending the natural regeneration, or enrichment planting followed by tending?
- 4) To what extent are the post-harvesting silvicultural treatments of tending natural regeneration and enrichment planting in logging gaps profitable in the long term?

Various research approaches were used to answer these questions. An experimental approach was used to measure the density and growth of seedlings, saplings, and poles of commercial species (Chapter 2; Chapter 3) after the forest had been harvested using RIL. As regeneration of commercial species is a limiting factor, the experiment described in Chapter 4 was carried out to evaluate two silvicultural treatments intended to improve the regeneration of commercial species. The long-term profitability of these treatments was calculated in Chapter 5, in a cost-benefit analysis with long-term projections.

In this synthesis the results are not discussed chapter by chapter following each question, but through the issues and findings present in different parts of the thesis.

Disturbances to the forest structure from RIL

The disturbances caused during logging operations in the studied forest were not homogeneously distributed. Logging usually creates a mosaic of micro-environments, ranging from a few highly disturbed areas to larger logged and unlogged areas subjected to low disturbance levels (Chapter 2). In this study the measurements carried out immediately after logging show that RIL directly affected 47.5% of all 2,438 sampled plots (size: 10 x 10 m), while only 5.9% were severely affected by logging, and 3.3% were affected by both logging and natural disturbances. The remaining 52.5% of the plots showed no direct effects of RIL. This corroborates the results of other studies reporting low levels of damage caused by RIL in tropical forests (Bertault and Sist, 1997; Pereira et al., 2002). Given that the negative effects of logging on the forest also depend on the volume harvested (Hendrison and De Graaf, 2011), the low levels of disturbance observed in Tapajós can be attributed to the strict application of RIL techniques and the relatively low timber volume harvested ($22 \text{ m}^3 \text{ ha}^{-1}$, which is about one-fifth of the timber volume available before logging).

Although the disturbance due to RIL operations was low, the investigated logged forest showed differences when compared to an adjacent untouched forest 1,200 m away. In the logged forest, the number of plots under mature-phase trees had decreased one year after logging, whereas the number of building- and gap-phase plots increased (Chi-square = 302.4, $p < 0.001$); the differences were still significant six years after logging (Chi-square = 7.6, $p < 0.02$; Chapter 3). Irrespective of these differences, a continuous shift of plots from gap- to building-phase and from building- to mature-phase was observed, as reported by Lopes (1993). Changes from the gap- to the building-phase are rapid, but shifts to mature-phase take longer, due to the time required for a tree to reach mature size ($\geq 45 \text{ cm}$, Chapter 3). This clearly shows that RIL disturbances have only a brief positive effect on growth rates (Silva et al., 1995; Silva et al., 1996). However, the timber volume of the harvested species may not return to the pre-logging levels (Sist and Ferreira 2007; Valle et al., 2007), even 28 years after logging, as observed by Reis et al. (2010) in another area in the Tapajós National Forest.

Effects of RIL on densities and growth rates of species from different functional groups

The seven commercial tree species studied in this thesis belong to three functional groups: 1) the long-lived pioneers (LLP) *Bagassa guianensis* and *Jacaranda copaia*; 2) the partially shade-tolerant (PST) *Hymenaea courbaril*, *Dipteryx odorata*, and *Carapa guianensis*; 3) and the totally shade-tolerant (TST) *Symphonia globulifera* and *Manilkara huberi*. These species were selected because they are widespread in the Amazon and are

representative of other commercial species in the region (Kanashiro et al., 2002; Chapter 2; Chapter 3).

In terms of density, as expected, no species except *J. copaia* showed variation in density of seedlings before logging (one year of measurements). One year after logging operations had ended, all species had increased in seedling density except *C. guianensis*, which slightly declined. The species *B. guianensis*, *J. copaia*, *H. courbaril*, and *D. odorata* increased their densities more than five times after logging. The post-logging increase in densities of seedlings was due to a steep increase in recruitment rates observed in *H. courbaril*, *D. odorata*, and *M. huberi*. On the other hand, overall mortality rates in both size classes considered here (individual trees < 300 cm tall and individual trees \geq 300 cm tall) only increased immediately after logging, reflecting direct influences of the harvesting operations. The results revealed that mortality due to logging operations was much less among larger plants than among smaller plants, but larger plants were more likely to be damaged, as reported for East Kalimantan, Indonesia (Bertault and Sist, 1997), and for Central America (Whitman et al., 1997).

Regarding functional groups, the long-lived pioneers (LLP) and most of the partially shade-tolerant (PST) species responded very positively to logging disturbances, notably by increasing their densities. These results are consistent with the findings of other studies (Lopes et al., 2001; Peña-Claros et al., 2008a; Swaine and Agyeman, 2008). The totally shade-tolerant (TST) species also increased in density after logging, indicating that RIL may also improve their recruitment rates, even under lower levels of disturbance. Nevertheless, the short-term increased densities of seedlings (improved regeneration) diminished over time, and had returned to pre-logging levels six years after logging, mainly because of lower light availability. The canopy openings closed gradually, growth decreased and seedling mortality rates increased (Chapter 3). A decrease in densities attributable to a steep increase in mortality and decrease in recruitment rates was also reported by Swaine and Agyeman (2008) for pioneer species in a tropical forest in Ghana.

The growth rates of all species increased in the first year after logging operations when compared to the control area, except for height growth in *M. huberi*. The same pattern was found in seedlings growing in the gap-phase plots, which had faster height growth rates than plants growing in building- or mature-phase plots. For saplings, this effect was observed only in *C. guianensis*; no differences were detected in diameter growth rates for the other species. In the medium term (6 years) growth rates returned toward pre-logging rates. Silva et al. (1995; 1996), in another area of the Tapajós National Forest, report an increase in

growth rates of adult trees only in the first three years after logging. After that, growth rates diminished, eventually reaching the same levels as observed in unlogged forests.

Regeneration of commercial tree species in the Eastern Amazon

Sufficient natural regeneration of commercial valuable tree species is an important requirement for sustainable forest management. Lack of regeneration of desirable species in managed tropical forests has been reported in the Western Brazilian Amazon (D'Oliveira, 2000a) and in Bolivia, especially for light-demanding species (Mostacedo and Fredericksen, 1999; Van Rheenen et al., 2004; Park et al., 2005). On the other hand, information on the conditions of the regeneration in managed forests in the Eastern Amazon is still limited (but see Lopes et al., 2001; Falkowski, 2011; Schwartz et al., 2012). In the 30 logging gaps assessed in the research described in this thesis (Chapter 4), seedlings and saplings from 50 commercial tree species (average of 8.57 ± 0.48 SE commercial species per gap) were found, although only one-third of these were harvested. In a similar study carried out in a logging compartment harvested in 2008 in Jari Valley, Falkowski (2011) reports that 48% of the species traded by the forestry company Orsa Florestal were present in the regeneration. The species found by Falkowski (2011) plus the species sampled in 30 logging gaps in this study give a total number of 15 species, which is 56% of the 27 species traded by Orsa Florestal. Not only in Jari but also in the Tapajós and in a third area (Rio Capim – 3°32'S – 48°35'W) a similar pattern was found, suggesting that there may be a lack of regeneration of commercial species in the Eastern Amazon (Falkowski, 2011; Schwartz et al., unpublished data). In these managed forests, some commercial species occur in small numbers or are even absent. The reasons for this shortage of natural regeneration and the ways to solve the problem are still unknown.

For mitigating such problems it has been suggested to apply post-harvesting silvicultural interventions in order to ensure sufficient regeneration of commercial species (Fredericksen and Pariona, 2002; Soriano et al., 2012). One such intervention would be to tend the naturally established regeneration in gaps (Pariona et al., 2003; Park et al. 2005), as gaps are an important environment for natural regeneration (Deslow, 1987). Besides tending the natural regeneration, silvicultural treatments may also include enrichment planting in gaps (Van Rheenen et al., 2004; Schulze, 2008; Doucet et al., 2009; Keefe et al., 2009). This treatment would artificially increase the densities of commercial species (D'Oliveira, 2000a; Lopes et al., 2008), as tested in this study (Chapter 4).

Post-harvesting silvicultural treatments

The insufficient regeneration of commercial species in tropical forests (D'Oliveira, 2000a; Mostacedo and Fredericksen, 1999; Van Rheenen et al., 2004; Park et al., 2005) could be mitigated by applying post-harvesting silvicultural treatments in gaps (Pariona et al., 2003; Fredericksen and Pariona, 2002; Soriano et al., 2012). In Chapter 4 the post-logging silvicultural treatments of tending naturally established seedlings and saplings (mainly by liberating the seedlings and saplings from competing non-commercial individuals and lianas) and enrichment planting in gaps created by RIL were tested. Both treatments were compared with a control site, in which individual trees received no silvicultural treatments. Four years of monitoring revealed that the silvicultural treatment of tending seedlings and saplings of commercial species naturally established in logging gaps was efficient. Mortality was lower and growth rates were higher than in enrichment planting followed by tending and by comparison with the control treatment. Even though these differences were not detected when the silvicultural treatments were compared using the most dominant individual per gap, the treatments did differ when a larger number of dominant individuals were taken into account (three or more dominant individuals per gap). When all planted or selected individuals were considered in the analysis, treatments also differed from each other, with seedlings and saplings of the tending treatment having lower mortality (Repeated measures ANOVA, $F_{2,61} = 10.0$, $p < 0.001$) and higher growth (ANCOVA, $F_{2,1749} = 16.7$, $p < 0.001$) rates.

Considering functional groups, the LLP species had a remarkably positive response in growth rates in both tending and in enrichment planting by comparison with the control measurement. But the results of tending and enrichment planting were not significantly different (Chapter 4). The PST species had the highest overall growth rate in the tending treatment and similar growth rates in the other two treatments. There were not sufficient individuals (at least 5 per treatment) to permit statistical comparisons of the TST species among silvicultural treatments. At the species level, responses were not homogenous. Some LLP species grew better in the treatment with liberation (*Goupia glabra* and *Laetia procera*), but others did not (*Jacaranda copaia* and *Jacaranda* sp.). The PST also showed heterogeneous responses: *Dinizia excelsa* and *Trattinnickia* sp. grew more than *Brosimum parinarioides*, *Humiria balsamifera*, *Qualea albiflora*, and *Tachigali myrmecophila* in treatments under liberation.

The reason that mortality increased in the control treatment was probably because individuals were overshadowed or outcompeted by taller trees around the gap or by the dominant individuals in the experiment. However, the enrichment planting with tending treatment still had the highest mortality rates at all measurement moments. Differences in initial mortality rates among the treatments could be due to the fact that many naturally established individuals were older than the planted ones. The high mortality rates in the enrichment planting treatment are due to a few species which had very high mortality: at the last assessment, the mortality rate was 64.5% for *Platymiscium filipes* and 33.6% for *Bagassa guianensis*.

The control of competition through liberation is an efficient method for increasing the growth rates of the regeneration (Pariona et al., 2003; Schulze, 2008). One more advantage of tending is that compared with enrichment planting, in this treatment less effort was required to liberate seedlings and saplings of non-commercial individuals and lianas (Repeated measures ANOVA, $F_{1,47} = 30.2$, $p < 0.001$). Over time, the percentage of individuals requiring liberation decreased in the tending treatment but increased in the enrichment planting treatment (Chapter 4).

Tending should only be applied in managed forests where there is sufficient natural regeneration of commercial species, especially of the most valuable ones. When commercial species are very low in number, or absent, the best option is enrichment planting. In this case, only seedlings of the highly valuable species should be planted, to maximize investments (Lamprecht, 1989; Chapter 5). Based on the results of four years of assessments, an important part of enrichment planting and tending is the choice of the species to be planted or tended: preference should be given to the species that respond best in growth, i.e. the fast-growing species (Tonini et al., 2008). Longer-term assessments of the experiment carried out in Jari, however, would give a better picture of the performance of slow-growing species (Reis et al., 2010) managed in logging gaps. Furthermore, enrichment planting using rare commercial species would also have the additional benefit of increasing densities of rare and important commercial tree species such as *Tabebuia* spp., *Hymenaea courbaril*, *Cordia goeldiana* and *Swietenia macrophylla* (Schulze et al., 2008). Enrichment planting would then also work as an important conservation tool (Jennings et al., 2001).

Profitability of post-harvesting silvicultural treatments in the Brazilian Amazon

The application of post-harvesting silvicultural treatments implies additional costs that are not currently accounted for in the standard RIL as practiced in the Brazilian Amazon

(MMA, 2006). Even though many authors recommend post-harvesting silvicultural treatments such as tending or enrichment planting (Pariona et al., 2003; Park et al., 2005; Schwartz et al., 2012; Soriano et al., 2012; Chapter 3; Chapter 4), few authors have addressed the costs and long-term future benefits of these treatments (Lopes et al, 2008; Schulze, 2008; Doucet et al., 2009; Keefe et al., 2009).

The profitability analysis of the two post-harvesting silvicultural treatments (enrichment planting and tending) carried out to assess their long-term profitability revealed that at interest rates of 3%, 6%, and 9%, neither treatment is profitable in the longer run. At an interest rate of 6%, all calculated values of the net present value (NPV) per hectare at 60 and 90 years (3rd and 4th cutting cycles) for both round- and sawnwood were negative. On the other hand, all calculated NPVs were positive for the standard RIL treatment, suggesting that the current management practice, in which logging gaps are left untreated, is the best long-term management option. Indeed, the high cost of enrichment planting has been a major hurdle to the adoption of this silvicultural treatment in tropical forests (Appanah and Weinland, 1996; Dupuy, 1998; Schulze 2008; Doucet et al., 2009).

It would, however, be possible to reduce the costs of enrichment planting and tending by liberating harvestable trees from competing individuals and lianas once a year instead of twice. Moreover, the cost of enrichment planting could be lowered by sowing seed directly (Lopes et al., 2008; Schulze, 2008; Doucet et al., 2009), wider planting spacing, and by planting or sowing in recent logging gaps where regeneration is not at an advanced stage. Preparing older logging gaps for planting was laborious and time-consuming, because here the regeneration was at an advanced stage and was mainly of pioneer species (G. Schwartz, personal observation; Chapter 4). Another way of increasing the profitability of the post-harvesting silvicultural treatments would be by cutting or girdling dominant but less valuable individuals in future interventions, to increase dominance of individuals of more valuable species. All these changes would drastically influence the long-term projections of profitability. A combination of reduced establishment and maintenance costs and a trend towards higher timber prices would also greatly improve the prospects for the profitability of these two post-harvesting silvicultural treatments. If these scenarios did come about, managed forest could become more competitive than other land uses (Keefe et al., 2012). It should also be remembered that the calculations in the cost-benefit analysis are based on current timber prices and costs of harvesting, which refer to the first cutting cycle, in which timber, including hardwood, is abundant and hence harvesting costs are low. However, future harvesting cycles would require more investments anyway, because pristine forests that can

be easily harvested are diminishing. Therefore, changes in tropical forest species composition and timber volumes would probably make investments in post-harvesting silvicultural treatments more profitable in the future.

Implications for forest management

Depending on their intensity, disturbances caused by logging may trigger an increase in the recruitment and growth rates of commercial tree species (Fredericksen and Putz, 2003), which might improve their regeneration. Nevertheless, such favourable effects are felt only in the first years after logging and disappear as the forest recovers (Silva et al., 1995; Swaine and Agyeman, 2008), which suggests that they are not sufficient to improve regeneration. The issue of short-time benefits of RIL and the possible lack of regeneration (Falkowski, 2011) would justify applying post-harvesting silvicultural treatments in the Eastern Amazon.

Tending naturally established seedlings and saplings in logging gaps is more efficient in terms of growth, mortality, and establishment costs (Chapter 4; Chapter 5) than the treatment that entails enrichment planting followed by tending. The latter treatment could nevertheless still be a good choice when there is not sufficient natural regeneration of commercial species (Lamprecht, 1989; Chapter 4). The two treatments might also be applied in the same management area, by applying tending wherever natural generation is available, and, when necessary, planting valuable and fast-growing species that are adapted to local conditions (Tonini et al., 2008; Gomes et al., 2010). The results presented in Chapter 5 imply that these treatments may still not be profitable in the long-term. A more careful application of the tending and enrichment planting techniques, giving priority to the most valuable and fast-growing species, would however increase profitability (Bais, 2012; Chapter 5). Another reason to expect that these silvicultural treatments will be more profitable in the future is that the trend of increasing timber prices is expected to continue (Pereira et al., 2010).

Once post-harvesting silvicultural treatments applied in logging gaps become more profitable than the standard RIL (with no post-harvesting silvicultural treatments at all), the polycyclic silvicultural system using RIL techniques for harvesting applied in the Brazilian Amazon will become a more financially interesting land use (Bacha and Rodriguez, 2007; Keefe et al., 2012). Consequently, forest management would become a more profitable alternative than other land uses that require deforestation (Walker and Homma, 1996; Hecht, 2011; De Espindola et al., 2012). Thus, the application of forest management would not only ensure long-term financial sustainability but would also allow the forest to continue to provide the full range of its environmental services.

References

- Alder, D., Silva, J.N.M., 2000. An empirical cohort model for management of *Terra Firme* forests in the Brazilian Amazon. *Forest Ecology and Management* 130, 141-157.
- Alves, J.C.Z.O., Miranda, I.S., 2008. Análise da estrutura de comunidades arbóreas de uma floresta amazônica de terra firme aplicada ao manejo florestal. *Acta Amazonica* 38, 657-666.
- Appanah, S., 1998. Management of natural forests. In: Appanah, S., Turnbull, J.M. (Eds.). *A review of dipterocarps: taxonomy, ecology and silviculture*. CIFOR, Bogor, pp. 133-141.
- Ashton, M., Hall, J.S., 2011. The ecology, silviculture, and use of tropical wet forests with special emphasis on timber rich types. In: Günter, S., Weber, M., Stimm, B., Mosandl, R. (Eds.). *Silviculture in the tropics*. Springer, Freising, pp. 145-192.
- Azevedo, C.P., 2006. Dinâmica de florestas submetidas a manejo na Amazônia Oriental: experimentação e simulação. PhD thesis, Federal University of Paraná, Curitiba, 236p.
- Azevedo, C.P., Sanquetta, C.R., Silva, J.N.M., Machado, S.A., 2008. Efeito da exploração de madeira e dos tratamentos silviculturais no agrupamento ecológico de espécies. *Floresta* 38, 53-69.
- Azevedo-Ramos, C., 2008. Sustainable development and challenging deforestation in the Brazilian Amazon: the good, the bad and the ugly. *Unasylva* 59, 12-16.
- Azevedo-Ramos, C.A., Carvalho Jr., O., Amaral, B.D., 2006. Short-term effects of reduced-impact logging on eastern Amazon fauna. *Forest Ecology and Management* 232, 26-35.
- Bacha, C.J.C., Rodriguez, C.E., 2007. Profitability and social impacts of reduced impact logging in the Tapajós National Forest, Brazil – A case study. *Ecological Economics* 63, 70-77.

References

- Bais, A.L.S., 2012. Profitability of post-harvesting silvicultural treatments in logging gaps in the Eastern Brazilian Amazon. MSc thesis, Wageningen University, Wageningen, 55p.
- Barreto, P., Amaral, P., Vidal, E., Uhl, C., 1998. Costs and benefits of forest management for timber production in eastern Amazonia. *Forest Ecology and Management* 108, 9-26.
- Becker, B.K., 2005. Geopolítica da Amazônia. *Estudos Avançados* 19, 71-86.
- Bertault, J.G., Sist, P., 1997. An experimental comparison of different harvesting intensities with reduced-impact and conventional logging in East Kalimantan, Indonesia. *Forest Ecology and Management* 94, 209-218.
- Blate, G.M., 2005. Modest trade-offs between timber management and fire susceptibility of a Bolivian semi-deciduous forest. *Ecological Applications* 15, 1649-1663.
- Boltz, F., Carter, D.R., Holmes, T.P., Pereira Jr., R., 2001. Financial returns under uncertainty for conventional and reduced-impact logging in permanent production forests of the Brazilian Amazon. *Ecological Economics* 39, 387-398.
- Brenes-Arguedas, T., Roddy, A.B., Coley, P.D., Kursar, T.A., 2011. Do differences in understory light contribute to species distributions along a tropical rainfall gradient? *Oecologia*, 166, 445-456.
- Brokaw, N.V.L., 1985. Gap-phase regeneration in a tropical forest. *Ecology* 66, 682-687.
- Carneiro, F.S., Degen, B., Kanashiro, M., Lacerda, A.E.B., Sebbenn, A.M., 2009. High levels of pollen dispersal detected through paternity analysis from a continuous *Symphonia globulifera* population in the Brazilian Amazon. *Forest Ecology and Management* 258, 1260-1266.
- Carneiro, F.S., Lacerda, A.E.B., Lemes, M.R., Gribel, R., Kanashiro, M., Wadt, L.H.O., Sebbenn, A.M., 2011. Effects of selective logging on the mating system and pollen dispersal of *Hymenaea courbaril* L. (Leguminosae) in the Eastern Brazilian Amazon as revealed by microsatellite analysis. *Forest Ecology and Management* 262, 1758-1765.
- Carvalho, J.O.P., Silva, J.N.M., Pokorny, B., Sabogal, C., Zweede, J., 2008. Systems for SFM. *Tropical Forest* 18, 9-11.

- Castro-Arellano, I., Presley, S.J., Willig, M.R., Wunderle, J.M., Saldanha, L.N., 2009. Reduced-impact logging and temporal activity of understorey bats in lowland Amazonia. *Biological Conservation* 142, 2131-2139.
- Clark, D.A., Clark, D.B., 1992. Life history diversity of canopy and emergent trees in a neotropical rain forest. *Ecological Monographs* 62, 315-344.
- Cloutier, D., Kanashiro, M., Ciampi, A.Y., Schoen, D.J., 2007. Impact of selective logging on inbreeding and gene dispersal in an Amazonian tree population of *Carapa guianensis* Aubl. *Molecular Ecology* 16, 797-809.
- Condit, R., Ashton, P.S., Manokaran, N., LaFrankie, J.V., Hubbell, P., Foster, R., 1999. Dynamics of the forest communities at Pasoh and Barro Colorado: comparing two 50-ha plots. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* 354, 1739-1748.
- Condit, R., Hubbell, S.P., Foster, R.B., 1993. Identifying fast-growing native trees from the Neotropics using data from a large, permanent census plot. *Forest Ecology and Management* 62, 123-143.
- D'Oliveira, M.V.N., 2000a. Artificial regeneration in gaps and skidding trails after mechanised forest exploitation in Acre, Brazil. *Forest Ecology and Management* 127, 67-76.
- D'Oliveira, M.V.N., 2000b. Sustainable forest management for small farmers in Acre State in the Brazilian Amazon. PhD thesis, University of Aberdeen, Aberdeen, 207p.
- D'Oliveira, M.V.N., Ribas, L.A., 2011. Forest regeneration in artificial gaps twelve years after canopy opening in Acre State Western Amazon. *Forest Ecology and Management* 261, 1722-1731.
- Dauber, E., Fredericksen, T.S., Peña, M., 2005. Sustainability of timber harvesting in Bolivian tropical forests. *Forest Ecology and Management* 214, 294-304.
- Dawkins, H.C., Philip, M.S., 1998. Tropical moist forest silviculture and management: a history of success and failure. CAB International, Eastbourne, 359p.

References

- De Espindola, G.M., De Aguiar, A.P.D., Pebesma, E., Câmara, G., Fonseca, L., 2012. Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data. *Applied Geography* 32, 240-252.
- De Graaf, N.R., 1986. A silvicultural system for natural regeneration of tropical rain forest in Suriname. Management of tropical rain forest in Suriname 1. PhD thesis, Wageningen University, Wageningen, 250p.
- De Graaf, N.R., Filius, A.M., Huesca Santos, A.R., 2003. Financial analysis of sustained forest management for timber perspectives for application of the CELOS management system in Brazilian Amazonia. *Forest Ecology and Management* 177, 287-299.
- De Graaf, N.R., Poels, R.L.H., Van Rompaey, R.S.A.R., 1999. Effect of silvicultural treatment on growth and mortality of rainforest in Surinam over long periods. *Forest Ecology and Management* 124, 123-135.
- De Graaf, N.R., Van Eldik, T., 2011. Precious Woods, Brazil. In: Werger, M.J.A. (Ed.), Sustainable Management of Tropical Rainforests: The CELOS Management System. Tropenbos Series 25, Paramaribo, pp. 186-199.
- Deslow, J.S., 1987. Tropical rainforest gaps and tree species diversity. *Annual Review of Ecology and Systematics* 18, 431-451.
- Doucet, J.L., Kouadio, Y.L., Monticelli, D., Lejeune, P., 2009. Enrichment of logging gaps with moabi (*Baillonella toxisperma* Pierre) in a Central African rain forest. *Forest Ecology and Management* 258, 2407-2415.
- Dupuy, B., 1998. Bases pour une sylviculture en forêt dense humide africaine. CIRAD-Forêt, Montpellier, 328p.
- Edwards, D.P., Woodcock, P., Edwards, F.A., Larsen, T.H., Hsu, W.W., Benedick, S., Wilcove, D., 2012. Reduced-impact logging and biodiversity conservation: a case study from Borneo. *Ecological Applications* 22, 251-271.
- Eva, H.D., Belward, A.S., Miranda, E.E., Bella, C.M., Gond, V., Huber, O., Jones, S., Sgrenzaroli, M., Fritz, S., 2004. A land cover map of South America. *Global Change Biology* 10, 731-744.

- Falkowski, V., 2011. Natural regeneration in forests under reduced-impact logging in the Eastern Brazilian Amazon. MSc thesis, Wageningen University, Wageningen, 28p.
- Fearnside, P.M., 2005. Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology* 19, 680-688.
- Fearnside, P.M., 2008. The roles and movements of actors in the deforestation of Brazilian Amazonia. *Ecology and Society* 13: 23. [online] URL: <http://www.ecologyandsociety.org/vol13/iss1/art23/>
- Felton, A., Felton, A.M., Wood, J., Lindenmayer, D.B., 2006. Vegetation structure, phenology, and regeneration in the natural and anthropogenic tree-fall gaps of a reduced-impact logged subtropical Bolivian forest. *Forest Ecology and Management* 235, 186-193.
- Field, A., 2005. *Discovering statistics using SPSS*. Sage, London, 779p.
- Foahom, B., Schmidt, P., 2011. Cameroon. In: Werger, M.J.A. (Ed.), *Sustainable Management of Tropical Rainforests: The CELOS Management System*, pp. 226-241. Tropenbos Series 25, Paramaribo, Suriname.
- Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., DeFries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2002. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Frontiers in Ecology and the Environment* 5, 25-32.
- Fox, J.E.D., 1976. Constrains on the natural regeneration of tropical moist forest. *Forest Ecology and Management* 1, 37-65.
- Fredericksen, T.S., Mostacedo, B., 2000. Regeneration of timber species following selection logging in a Bolivian tropical dry forest. *Forest Ecology and Management* 131, 47-55.
- Fredericksen, T.S., Pariona, W., 2002. Effect of skidder disturbance on commercial tree regeneration in logging gaps in a Bolivian tropical forest. *Forest Ecology and Management*, 171, 223-230.

References

- Fredericksen, T.S., Putz, F.S., 2003. Silvicultural intensification for tropical forest conservation. *Biodiversity and Conservation* 12, 1445-1453.
- Garda, A.A., Da Silva, J.M.C., Baião, P.C., 2010. Biodiversity conservation and sustainable development in the Amazon. *Systematics and Biodiversity* 8, 169-175.
- Gerwing, J.J., 2002. Degradation of forests through logging and fire in the eastern Brazilian Amazon. *Forest Ecology and Management* 57, 131-141.
- Gomes, J.M., Carvalho, J.O.P., Da Silva, M.G., Nobre, D.N.V., Taffarel, M., Ferreira, J.E.R., Santos, R.N.J. 2010. Sobrevivência de espécies arbóreas plantadas em clareiras causadas pela colheita de madeira em uma floresta de terra firme no município de Paragominas na Amazônia brasileira. *Acta Amazonica* 40, 171-178.
- Gómez, J.W.L., 2011. Regeneración natural de nueve especies maderables en un bosque intervenido de la Amazonia Boliviana. *Acta Amazonica* 41, 135-142.
- Grogan, J.S., Jennings, S.B., Landis, R.M, Schulze, A., Baima, A.M.V., Lopes, J.C.A., Norghauer, J.M., Oliveira, L.R., Pantoja, F., Pinto, D., Silva, J.N.M., Vidal, E., Zimmerman, B.L., 2008. What loggers leave behind: impacts on big-leaf mahogany (*Swietenia macrophylla*) commercial populations and potential for post-logging recovery in the Brazilian Amazon. *Forest Ecology and Management* 255, 269-281.
- Guariguata, M.R., Dupuy, J.M., 1997. Forest regeneration in abandoned logging roads in lowland Costa Rica. *Biotropica* 29, 15-28.
- Hawthorne, W.D., Sheil, D., Agyeman, V.K., Abu Juam, M., Marshall, C.A.M., 2012. Logging scars in Ghanaian high forest: Towards improved models for sustainable production. *Forest Ecology and Management* 271, 27-36.
- Hecht, S.B., 2011. From eco-catastrophe to zero deforestation? Interdisciplinarity, politics, environmentalisms and reduced clearing in Amazonia. *Environmental Conservation* 39, 4-19.
- Hendrison, J., De Graaf, N.R., 2011. History of use and management of forests in Suriname. In: Werger, M. J. A. (Ed.), *Sustainable Management of Tropical Rainforests: The CELOS Management System*. Tropenbos Series 25, Paramaribo, pp. 9-28.

- Henriques, R.P.B., Sousa, E.C.E.G., 1989. Population structure, dispersion and microhabitat regeneration of *Carapa guianensis* in northeastern Brazil. *Biotropica* 21, 204-209.
- Herrero-Jáuregui, C., García-Fernández, C., Sist, P.L.J., Casado, M.A., 2011. Recruitment dynamics of two low-density neotropical multiple-use tree species. *Plant Ecology* 212, 1501-1512.
- Holmes, T.P., Blate, G.M., Zweede, J.C., Pereira Jr., R., Barreto, P., Boltz, F., Bauch, R., 2002. Financial and ecological indicators of reduced impact logging performance in the eastern Amazon. *Forest Ecology and Management* 163, 93-110.
- Homma, A.K.O., 2005. Amazônia: como aproveitar os benefícios da destruição? *Estudos Avançados* 19, 115-135.
- Huth, A., Ditzer, T., 2001. Long-term impacts of logging in a tropical rain forest – a simulation study. *Forest Ecology and Management* 142, 33-51.
- IBGE (Instituto Brasileiro de Geografia e Estatística), 2004. Mapa de Vegetação do Brasil. [online] URL: <http://www.ibge.gov.br/home/presidencia/noticias/21052004biomas.shtm> (accessed on 15 September 2012).
- Imai, N., Samejima, H., Langner, A., Ong, R.C., Kita, S., Titin, J., Chung, A.Y.C., Lagan, P., Lee, Y.F., Kitayama, K., 2009. Co-benefits of sustainable forest management in biodiversity conservation and carbon sequestration. *PLoS ONE* 4: e8267. doi: 10.1371/journal.pone.0008267
- INPE (Instituto Nacional de Pesquisas Espaciais), 2012. Projeto PRODES: Monitoramento da Floresta Amazônica por Satélite. [online] URL: http://www.obt.inpe.br/prodes/prodes_1988_2011.htm (accessed on 15 September 2012).
- Jackson S.M., Fredericksen T.S., Malcolm J.R., 2002. Disturbance and residual stand damage following selection logging in a Bolivian tropical forest. *Forest Ecology and Management* 166, 271–283.
- Jansen, P.A., Zuidema, P.A., 2001. Logging, seed dispersal by vertebrates, and natural regeneration of tropical timber trees. In: Fimbel, R.A., Robinson, J.G., Grajal, A. (Eds.),

References

- The cutting edge: conserving wildlife in logged tropical forests. Columbia University Press, New York, pp. 35-59.
- Jennings, S.B., Brown, N.D., Boshier, D.H., Whitmore, T.C., Lopes, J.C.A., 2001. Ecology provides a pragmatic solution to the maintenance of genetic diversity in sustainably managed tropical rain forests. *Forest Ecology and Management* 154, 1-10.
- JohnS, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. *Forest Ecology and Management* 89, 59-77.
- Jonkers, W.B.J., Hendrison, J., 2011. The CELOS Management System: concept, treatments and costs. In: Werger, M. J. A. (Ed.), *Sustainable Management of Tropical Rainforests: The CELOS Management System*. Tropenbos Series 25, Paramaribo, pp. 29-45.
- Kanashiro, M., Thompson, I.S., Yared, J.A.G., Loveless, M.D., Coventry, P., Martins-da-Silva, R.C.V., Degen, B., Amaral, W., 2002. Improving conservation values of managed forest: the Dendroge project in the Brazilian Amazon. *Unasyuva* 53, 25-33.
- Keefe, K., Alavalapati, J.A.A., Pinheiro, C., 2012. Is enrichment planting worth its costs? A financial cost-benefit analysis. *Forest Policy and Economics* 23, 10-16.
- Keefe, K., Schulze, M.D., Pinheiro, C., Zweede, J.C., Zarin, D., 2009. Enrichment planting as a silvicultural in the eastern Amazon: a case study of Fazenda Cauaxi. *Forest Ecology and Management* 258, 1950-1959.
- Klimas, C.A., Kaimer, K.A., Wadt, L.H.O., 2007. Population structure of *Carapa guianensis* in two forest types in the southwestern Brazilian Amazon. *Forest Ecology and Management* 250, 256-265.
- Kohlhepp, G., 2000. Amazonia 2000: an evaluation of three decades of regional planning and development programmes in the Brazilian amazon region. *Amazoniana* 3-4, 363-395.
- Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources* 28, 205-241.

- Kuusipalo, J., Jafarsidik, Y., Adjers, G., Tuomela, K., 1996. Population dynamics of tree seedlings in a mixed deipterocarp rainforest before and after logging and crown liberation. *Forest Ecology and Management* 81, 85-94.
- Lamprecht, H., 1989. *Silviculture in the tropics*. GTZ, Eschborn, 296p.
- Laurance, W.F., Albernaz, A.K.M., Schroth, G., Fearnside, P.M., Bergen, S., Venticinque, E.M., Costa, C., 2002. Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography* 29, 737-748.
- Lentini, M., Pereira, D., Celentano, D., Pereira, R., 2005. *Fatos florestais da Amazônia 2005*. Imazon, Belém, 138p.
- Lins, C., 1991. *Jari 70 anos de história*. Dataforma, Rio de Janeiro, 236p.
- Livingstone, I., Tribe, M., 1995. Projects with long time horizons: their economic appraisal and the discount rate. *Project Appraisal* 10, 66-76.
- Lopes, J.C.A. 1993. *Demografia e flutuações temporais da regeneração após uma exploração florestal: Flona do Tapajós-PA*. MSc thesis, ESALQ-USP, Piracicaba, 133p.
- Lopes, J.C.A., Jennings, S.B., Matni, N.M., 2008. Planting mahogany in canopy gaps created by commercial harvesting. *Forest Ecology and Forest Management* 255, 300-307.
- Lopes, J.C.A., Whitmore, T.C., Brown, N.D., Jennings, S.B., 2001. Efeito da exploração florestal nas populações de mudas em uma floresta tropical úmida no município de Moju, PA. In: Silva, J.N.M., Carvalho, J.O.P., Yared, J.A.G. (Eds.), *Silvicultura na Amazônia Oriental: contribuições do projeto Embrapa/DFID*. Embrapa Amazônia Oriental/DFID, Belém, pp. 203-226.
- Losos, E.C., Lao, S.L., 2004. Forest dynamics plots. In: Losos, E.C., and Leigh Jr., E.G. (Eds.), *Tropical forest diversity and dynamism: findings from a large-scale plot network*. The University of Chicago Press, Chicago, pp. 433-450.
- Macpherson, A.J., Carter, D.R., Schulze, M.D., Vidal, E., Lentini, M.W., 2012. The sustainability of timber production from Eastern Amazonian forests. *Land Use Policy* 29, 339-350.

References

- Matthews, J.D., 1989. *Silvicultural systems*. Oxford Science, Suffolk, 285p.
- Maues, M.M., 2006. Estratégias reprodutivas de espécies arbóreas e sua importância para o manejo e conservação: Floresta Nacional do Tapajós (Belterra-PA). PhD thesis, University of Brasília, Brasília, 209p.
- Medjibe, V.P., Putz, F.E., 2012. Cost comparisons of reduced-impact and conventional logging in the tropics. *Journal of Forest Economics* 18, 242-256.
- Mello-Ivo, W.M.P., Ross, S., 2006. Efeito da colheita seletiva de madeira sobre algumas características físicas de um latossolo amarelo sob floresta na Amazônia central. *Revista Brasileira da Ciência do Solo* 30, 769-776.
- Meyfroidt, P., Lambin, E.F., 2011. Global forest transition: prospects for an end to deforestation. *Annual Review of Environment and Resources* 36, 343-371.
- Miller, S.D., Goulden, M.L., Hutrya, L.R., Keller, M., Saleska, S.R., Wofsy, S.C., Figueira, A.M.S., Da Rocha, H.R., De Camargo, P.B., 2011. Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. *Proceedings of the National Academy of Sciences* 108, 19431-19435.
- Miller, S.D., Goulden, M.L., Da Rocha, H.R., 2007. The effect of canopy gaps on subcanopy ventilation and scalar fluxes in a tropical forest. *Agricultural and Forest Meteorology* 142, 25-34.
- Mittermeier, R.A., Mittermeier, C.G., Brooks, T.M., Pilgrim, J.D., Konstant, W.R., Fonseca, G.A.B., Kormos, C., 2003. Wilderness and biodiversity conservation. *Proceedings of the National Academy of Sciences* 100, 10309-10313.
- MMA, 2006. Instrução Normativa N° 5 de 11 de dezembro de 2006. Ministry of Environment (MMA) – Brazil. [online] URL: www.mma.org.br (accessed on 26 November 2011).
- Monteiro, A.L.S., Souza Jr., C.M., Barreto, P.G., Pantoja, F.L.S., Gerwing, J.J., 2004. Impactos da exploração madeireira e do fogo em florestas de transição da Amazônia Legal. *Scientia Forestalis* 65, 11-21.

- Montgomery, R., Chazdon, R., 2002. Light gradient partitioning by tropical tree seedlings in the absence of canopy gaps. *Oecologia* 131, 165-174.
- Mostacedo, B., Fredericksen, T.S., 1999. Regeneration status of important tropical forest tree species in Bolivia: assessment and recommendations. *Forest Ecology and Management* 124, 263-273.
- Nabe-Nielsen, J., Severiche, W., Fredericksen, T., Nabe-Nielsen, L.I., 2007. Timber tree regeneration along abandoned logging roads in a tropical Bolivian forest. *New Forests* 34, 31-40.
- Navarro-Cerillo, R.M., Griffith, D.M., Ramírez-Soria, M.J., Pariona, W., Golicher, D., Palacios, G., 2011. Enrichment of big-leaf mahogany (*Swietenia macrophylla* King) in logging gaps in Bolivia: the effects of planting method and silvicultural treatments on long-term seedling survival and growth. *Forest Ecology and Management* 262, 2271-2280.
- Nepstad, D.C., Sickler, C.M., Soares-Filho, B., Merry, F., 2008. Interactions among Amazon land use, forests and climate: prospects for a near-term tipping point. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* 363, 1737-1746.
- Nicotra, A.B., Chazdon, R.L., Iriarte, V.B., 1999. Spatial heterogeneity of light and woody seedling regeneration in tropical wet forests. *Ecology* 80, 1908-1926.
- Nyland, R.D., 1996. Silviculture concepts and applications. McGraw-Hill, New York, 633p.
- Ohlson-Kiehn, C., Pariona, W., Fredericksen, T.S., 2006. Alternative tree girdling and herbicide treatment for liberation and timber stand improvement in Bolivian tropical forests. *Forest Ecology and Management* 225, 207-212.
- Orsa Florestal, 2012. [online] URL: <http://www.orsaflorestal.com.br/> (accessed on 16 August 2012).
- Pakhriazad, H.Z., Mohd Hasmadi, I., Gerten, U.R., 2010. The effects of reduced impact logging (RIL) on Forest regeneration in Ulu Baram, Sarawak, Malaysia. *Malaysian Forester* 73, 111-121.

References

- Pariona, W., Fredericksen, T.S., Licona, J.C., 2003. Natural regeneration and liberation of timber species in logging gaps in two Bolivian tropical forests. *Forest Ecology and Management* 181, 313-322.
- Park, A., Justiniano, M.J., Fredericksen, T.S., 2005. Natural regeneration and environmental relationships of tree species in logging gaps in a Bolivian tropical forest. *Forest Ecology and Management* 217, 147-157.
- Peña-Claros, M., Peters, E.M., Justiniano, M.J., Bongers, F., Blate, G.M., Fredericksen, T.S., Putz, F.E., 2008a. Regeneration of commercial tree species following silvicultural treatments in a moist tropical forest. *Forest Ecology and Management* 255, 1283-1293.
- Peña-Claros, M., T.S. Fredericksen, A. Alarcón, G.M. Blate, U. Choque, C. Leño, J.C. Licona, B. Mostacedo, W. Pariona, F.E. Putz. 2008b. Beyond reduced-impact logging: silvicultural treatments to increase growth rates of tropical trees. *Forest Ecology and Management* 256: 1458-1467.
- Pereira, D., Santos, D., Vedoveto, M., Guimarães, J., Veríssimo, A., 2010. Fatos Florestais da Amazonia 2010. Imazon, Belém, 122p.
- Pereira, R., Zweede, J., Asner, G.P., Keller, M., 2002. Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Pará, Brazil. *Forest Ecology and Management* 168, 77-89.
- Phillips, P.D., Azevedo, C.P., Degen, B., Thompson, I.S., Silva, J.N.M., Van Gardingen, P.R., 2004. An individual-based spatially explicit simulation model for strategic forest management planning in the eastern Amazon. *Ecological Modelling* 173, 335-354.
- Pinard, M.A., Putz, F.E., 1996. Retaining forest biomass by reducing logging damage. *Biotropica* 28, 278-295.
- Poorter, L., Bongers, L., Bongers, F., 2006. Architecture of 54 moist-forest tree species: traits, trade-offs, and functional groups. *Ecology* 87, 1289-1301.
- Presley, S.J., Willig, M.R., Saldanha, L.N., Wunderle, J.M., Castro-Arellano, I., 2009. Reduced-impact logging has little effect on temporal activity of frugivorous bats (Chiroptera) in lowland Amazonia. *Biotropica* 41, 369-378.

- Putz, F.E., Sist, P., Fredericksen, T., Dykstra, D., 2008. Reduced-impact logging: challenges and opportunities. *Forest Ecology and Management* 256, 1427-1433.
- Reis, L.P., Ruschel, A.D., Coelho, A.A., Luz, A.S., Martins-da-Silva, C.V., 2010. Avaliação do potencial madeireiro na Floresta Nacional do Tapajós, após 28 anos da exploração florestal. *Pesquisa Florestal Brasileira* 30, 265-281.
- Rice, A.H., Pyle, E.H., Saleska, S.R., Hutyra, L., Palace, M., Keller, M., De Camargo, P.B., Portilho, K., Marques, D.F., Wofsy, S.C., 2004. Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecological Applications*, 14 Supplement, S55-S71.
- Rodrigues, A.S.L., Ewers, R.M, Parry, L., Souza Jr., C., Veríssimo, A., Balmford, A., 2009. Boom-and-bust development patterns across the Amazon deforestation frontier. *Science* 324, 1435-1437.
- Row, C., Kaiser, H.F., Sessions, J., 1981. Discount rate for long-term forest service investments. *Journal of Forestry* 79, 367-376.
- Sablayrolles, P., Drigo, I., Barthelon, S., Espada, A.L.V., De Blas, D.E., Piketty, M.G., 2011. O manejo florestal sustentável como alternativa na reprodução social de comunidades no oeste paraense? In Cruz, H., Sablayrolles, P., Kanashiro, M., Amaral, M., Sist, P. (Eds.), *Relação empresa-comunidade no contexto do manejo florestal comunitário e familiar: uma contribuição do projeto Florest em Pé*. IBAMA/MMA, Belém, Brazil, pp. 149-170.
- Schulze, M. D., 2003. Ecology and behavior of nine timber tree species in Pará, Brazil: Links between species life history and forest management and conservation. PhD thesis, The Pennsylvania State University, University Park, 126p.
- Schulze, M., 2008. Technical and financial analysis of enrichment planting in logging gaps as a potential component of forest management in the eastern Amazon. *Forest Ecology and Management* 255, 866-879.
- Schulze, M., Grogan, J., Landis, R.M., Vidal, E., 2008a. How rare is too rare to harvest? Management challenges posed by timber species occurring at low densities in the Brazilian Amazon. *Forest Ecology and Management* 256, 1443-1457.

References

- Schulze, M., Grogan, J., Uhl, C., Lentini, M., Vidal, E., 2008b. Evaluating ipê (*Tabebuia*, Bignoniaceae) logging in Amazonia: Sustainable management or catalyst for forest degradation? *Biological Conservation* 141, 2071-2085.
- Schulze, M., Lentini, M.W., Macpherson, J., Grogan, J., 2010. Certification, concessions and biodiversity in the Brazilian Amazon. *ETFRN News* 51, 83-89.
- Schwartz, G., Peña-Claros, M., Lopes, J.C.A., Mohren, G.M.J., Kanashiro, M., 2012. Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon. *Forest Ecology and Management* 274, 116-125.
- Sebbenn, A.M., Degen, B., Azevedo, V.C.R., Silva, M.B., Lacerda, A.E.B., Ciampi, A.Y., Kanashiro, M., Carneiro, F.S., Thompson, I., Loveless, M.D., 2008. Modelling the long-term impacts of selective logging on genetic diversity and demographic structure of four tropical tree species in the Amazon forest. *Forest Ecology and Management* 254, 335–349.
- SEMA (Secretaria de Estado de Meio Ambiente), 2012. Espécies Florestais em Toras na GF1 (Marketing of wood products via GF1). Extração e Movimentação de Toras de Madeira Nativa. Governo de Estado do Pará. Período de 1-1-2006 até 4-12-2011. [online] URL: <http://www.monitoramento.sema.pa.gov.br> (accessed on 13 September 2012).
- SFB/IMAZON, 2010. A atividade madeireira na Amazônia brasileira: produção, receita e mercados. Serviço Florestal Brasileiro/Instituto do Homem e Meio Ambiente da Amazônia, Belém, 26p.
- Shearman, P., Bryan, J., Laurance, W.F., 2012. Are we approaching “peak timber” in the tropics? *Biological Conservation* 151, 17-21.
- Sheil, D., Burslem, D.F.R.P., Alder, D., 1995. The interpretation and misinterpretation of mortality measures. *Journal of Ecology* 83, 331-333.
- Silva, J.N.M., 1989. The behaviour of the tropical rain forest of the Brazilian Amazon after logging. PhD thesis, University of Oxford, Oxford, 302p.
- Silva, J.N.M., 1997. Manejo de florestas de terra firme na Amazônia brasileira. In: EMBRAPA-CNPQ. Tópicos em manejo florestal sustentável. Documentos 34, 59-96.

- Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., 1985. Inventário florestal de uma área experimental na Floresta Nacional do Tapajós. *Boletim de Pesquisa Florestal* 10-11, 38-110.
- Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Almeida, B.F., Costa, D.H.M., Oliveira, L.C., Vancley, J.K., Skovsgaard, J.P., 1995. Growth and yield of a tropical rainforest in the Brazilian Amazon 13 years after logging. *Forest Ecology and Management* 71, 267-274.
- Silva, J.N.M., Carvalho, J.O.P., Lopes, J.C.A., Oliveira, R.P., Oliveira, L.C., 1996. Growth and yield studies in the Tapajós region, Central Brazilian Amazon. *Commonwealth Forestry Review* 75, 325-329.
- Silva, M.B., Kanashiro, M., Ciampi, A.Y., Thompson, I., Sebbenn, A.M., 2008. Genetic effects of selective logging and pollen gene flow in a low-density population of the dioecious tropical tree *Bagassa guianensis* in the Brazilian Amazon. *Forest Ecology and Management* 255, 1548-1558.
- Sist, P., Brown, N., 2004. Silvicultural intensification for tropical forest conservation: a response to Fredericksen and Putz. *Biodiversity and Conservation* 13, 2381-2385.
- Sist, P., Ferreira, F.N., 2007. Sustainability of reduced-impact logging in the Eastern Amazon. *Forest Ecology and Management* 243, 199-209.
- Sist, P., Nguyen-Thé, N., 2002. Logging damage and the subsequent dynamics of dipterocarp forest in East Kalimantan (1990-1996). *Forest Ecology and Management* 165, 85-103.
- Soriano, M., Kainer, K.A., Staudhammer, C.L., Soriano, E., 2012. Implementing multiple forest management in Brazil nut-rich community forests: Effects of logging on natural regeneration and forest disturbance. *Forest Ecology and Management* 268, 92-102.
- Steel, R.G.D., Torrie, J.H., 1981. Principles and procedures of statistics: a biometrical approach. McGraw-Hill, Singapore, 633p.
- Swaine, M.D., Agyeman, V.K., 2008. Enhanced tree recruitment following logging in two forest reserves in Ghana. *Biotropica* 40, 370-374.

References

- Toledo-Aceves, T., Purata-Velarde, S., Peters, C.M., 2009. Regeneration of commercial tree species in a logged forest in the Selva Maya, Mexico. *Forest Ecology and Management* 258, 2481-2489.
- Tonini, H, Costa, P., Kaminski, P.E., 2009. Estrutura, distribuição espacial e produção de sementes de andiroba (*Carapa guianensis* Aubl.) no sul do estado de Roraima. *Ciência Florestal* 19, 1-8.
- Tonini, H., Oliveira Jr., M.M.C.O., Schwenger, D., 2008. Crescimento de espécies nativas da Amazônia submetidas ao plantio no estado de Roraima. *Ciência Florestal* 18, 151-158.
- Uhl, C., Vieira, I.C.G., 1989. Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. *Biotropica* 21, 98-106.
- Valle, D., Phillips, P., Vidal, E., Schulze, M., Grogan, J., Sales, M., Gardingen, P., 2007. Adaptation of a spatially explicit individual tree-based growth and yield model and long-term comparison between reduced impact and conventional logging in Eastern Amazonia, Brazil. *Forest Ecology and Management* 243, 187-198.
- Van Gardingen, P.R., Valle, D., Thompson, I., 2006. Evaluation of yield regulation options for primary forest in Tapajós National Forest, Brazil. *Forest Ecology and Management* 231, 184-195.
- Van Rheenen, H.M.P.J.P., Boot, R.G.A., Werger, M.J.A., Ulloa, M.U., 2004. Regeneration of timber trees in a logged tropical forest in North Bolivia. *Forest Ecology and Management* 200, 39-48.
- Veloso, H.P., Rangel Filho, A.L.R., Lima, J.C.A., 1991. Classificação da vegetação brasileira adaptada a um sistema universal. IBGE, Rio de Janeiro, 123p.
- Verissimo, A., Barreto, P., Mattos, M., Tarifa, R., Uhl, C., 1992. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: The case of Paragominas. *Forest Ecology and Management*, 55, 169-199.

- Verwer, C., Peña-Claros, M., Van Der Staak, D., Ohlson-Kiehn, K., Sterck, F.J., 2008. Silviculture enhances the recovery of overexploited mahogany *Swietenia macrophylla*. *Journal of Applied Ecology*, 45, 1770-1779.
- Wadsworth, F.H., Zweede, J.C., 2006. Liberation: acceptable production of tropical forest timber. *Forest Ecology and Management* 233, 45-51.
- Walker, R., Homma, A.K.O., 1996. Land use and land cover dynamics in the Brazilian Amazon: an overview. *Ecological Economics* 18, 67-80.
- Watrin, O.S., 2003. Dinâmica da paisagem em projetos de assentamentos rurais no Sudeste Paraense utilizando geotecnologias. PhD thesis, Federal University of Rio de Janeiro, Rio de Janeiro, 209p.
- Whitman, A. A., Brokaw, N.V.L., Hagan, J.M., 1997. Forest damage caused by selection logging of mahogany (*Swietenia macrophylla*) in northern Belize. *Forest Ecology and Management* 92, 87-96.
- Whitmore, T.C., 1982. On pattern and process in forests. In: Newman, E.I. (Ed.). *The plant community as a working mechanism*. Blackwell Scientific, Oxford, pp. 45-49.
- Whitmore, T.C., 1984. *Tropical rain forest of the far East*. Oxford University Press, Oxford, 352p.
- Wunderle Jr., J.M., Henriques, L.M.P., Willing, M.R., 2006. Short-term responses of birds to forest gaps and understorey: an assessment of reduced-impact logging in a lowland Amazon forest. *Biotropica* 38, 235-255.
- Yared, J.A.G., Carvalho, J.O.P., Silva, J.N.M., Kanashiro, M., Marques, L.C.T., 2000. Contribuições do Projeto Silvicultura Tropical – Cooperação internacional Brasil/Reino Unido. Embrapa Amazônia Oriental/DFID, Belém, 28p.
- Zarin, D.J., Schulze, M.D., Vidal, E., Lentini, M., 2007. Beyond reaping the first harvest: management objectives for timber production in the Brazilian Amazon. *Conservation Biology* 21, 916-925.

References

Summary

The Amazon encompasses approximately 60% of all remaining tropical rainforests of the world and most of its area is in Brazilian territory, where nearly 20% of the forest cover has been lost due to deforestation. Forest management in the Brazilian Amazon started experimentally in the 1970s, when the Malayan Uniform System was adapted to local conditions by being made a polycyclic silvicultural system; later, elements of the CELOS system were included. The harvesting techniques were also improved with the introduction of reduced-impact logging (RIL) techniques. RIL is more environmentally-friendly than conventional logging, having low or no impact on wildlife and populations of harvested tree species. Some studies, however, show that forests managed under the current practices may not have enough regeneration of commercial species and that the harvested species will have lower timber yields in future cutting cycles. Among the possible options for mitigating these problems is the application of post-harvesting silvicultural treatments. Promising candidates are the tending of the naturally established regeneration by diminishing competition with lianas and other commercially less valuable trees, and enrichment planting in gaps created by RIL. These treatments, however, require long-term financial investments, which might reduce their profitability. On the other hand, they may also add value to the forests, thereby enabling managed forest to compete better with other land uses, which have a more negative impact on forest cover.

In this thesis the following questions were addressed: 1) How does the regeneration of commercial tree species respond to the different levels of disturbances created by RIL? 2) How does the regeneration of commercial tree species respond in the medium term to disturbances caused by RIL? 3) Which of the two post-harvesting silvicultural treatments applied in logging gaps is most suitable: tending the natural regeneration, or enrichment planting followed by tending? 4) To what extent are the post-harvesting silvicultural treatments of tending natural regeneration and enrichment planting in logging gaps profitable in the long term?

The short-term effect of RIL on the regeneration of seven commercial tree species was assessed in Chapter 2, through an experiment carried out in an intensively studied plot in the 600,000 ha Tapajós National Forest, eastern Amazon, Brazil. The species studied belong to three functional groups: the long-lived pioneers (LLP) *Bagassa guianensis* and *Jacaranda*

Summary

copaia; the partially shade-tolerant (PST) *Hymenaea courbaril*, *Dipteryx odorata*, and *Carapa guianensis*; and the totally shade-tolerant (TST) *Symphonia globulifera* and *Manilkara huberi*. All individuals of these species that were < 20 cm in diameter were inventoried and measured three times (in 2002-2003) before logging and then twice after logging (in 2003-2004). The logged area was sampled through 28 transects consisting of 10 x 10 m plots, covering 24.39 ha in total. The average intensity of harvesting was 22 m³ ha⁻¹ (21% of the original commercial volume). In Chapter 3 it is evaluated the medium-term effects of RIL, part of these harvested transects were measured twice more (in 2006 and 2009) and compared with another three transects established in an unlogged adjacent forest and also measured in 2006 and 2009 (total area measured was 2.37 ha).

Chapter 4 describes the research carried out in the forest management area of the Orsa Florestal forestry company in Jari Valley, in eastern Amazon, Brazil. Here, 64 2-year-old logging gaps with an average size of 427.2 m² were sampled. In 34 of these gaps the enrichment planting treatment was applied, 15 gaps underwent the tending treatment, and the remaining 15 were used as control. The mortality and growth rates of the monitored individual trees were measured for four years. In Chapter 5, the responses of individual trees to the tending and enrichment planting treatments were extrapolated in the long term (60 and 90 years) to evaluate timber production and profitability. The two silvicultural treatments were compared to a control treatment representing the standard current procedures of RIL (when gaps have no post-harvesting treatments), assuming different long-term interest rates, rising prices for round- and sawnwood, and increasing harvesting costs.

The results show that RIL did not have a destructive effect on the harvested forest: 52.5% of the area remained untouched and only 9.2% was highly disturbed by logging operations. All species except *C. guianensis* increased in density after logging. The LLP species mainly increased in density in highly disturbed plots, whereas the PST and TST species increased in density in logged plots under low disturbance levels. The positive effect of increasing densities of the harvested species was ephemeral and had disappeared two years after logging, but the modified forest structure was still discernable after 6 years. RIL had a positive effect on the height growth rate of *S. globulifera* and on the diameter growth rate of *C. guianensis*. Plants growing in disturbed plots had faster height growth rates than plants growing in the undisturbed plots, but the same pattern was not observed for the diameter growth rates.

Of the 10 species analysed, five (the LLP *Goupia glabra* and *Laetia procera*, and the PST *Dinizia excelsa*, *Tachigali myrmecophila*, and *Trattinnickia* sp.) responded positively to silvicultural treatments. Based on these results, the treatment of tending is recommended for areas of logged tropical forest with sufficient natural regeneration of commercial species. The enrichment planting treatment should be applied using only species with high initial growth rates and commercial value. Neither tending nor enrichment planting was profitable under the long-term interest rates of 3%, 6%, and 9% and only sawnwood produced through tending under a 750% increase of timber prices in 60 years would make the treatment profitable. Reduction in costs and improvements in the tending and enrichment planting techniques would nonetheless make these post-harvesting silvicultural treatments profitable for both round- and sawnwood. Once having these treatments more profitable, managed forest will be a more economically competitive land use in the Amazon.

Summary

Samenvatting

Het Amazonewoud omvat ongeveer 60% van alle resterende tropische regenbossen van de wereld. Het grootste deel van dit gebied bevindt zich op het Braziliaanse grondgebied. Als gevolg van houtkap is er echter bijna 20% van het bosareaal verloren gegaan. Bosbeheer in het Braziliaanse Amazonegebied begon experimenteel in de jaren 1970, toen het ‘Malaysian Uniform System’ aangepast werd aan lokale omstandigheden door er een polycyclische bosbeheerssysteem van te maken; later werden elementen van het CELOS systeem, zoals ontwikkeld in Suriname, erin opgenomen. De oogsttechnieken werden ook verbeterd met de introductie van Reduced-Impact Logging (RIL) technieken. RIL is milieuvriendelijker dan conventionele houtkap, met weinig of geen invloed op biodiversiteit en op de populaties van de geoogste boomsoorten. Sommige studies tonen echter aan dat de huidige beheerpraktijk niet genoeg verjonging van commerciële soorten vertonen, en dat de opbrengsten van de geoogste soorten kleiner zijn in toekomstige kapcycli. Een van de mogelijke opties voor het beperken van deze problemen is het toepassen van bosbouwkundige behandelingen na de oogst. Veelbelovende opties zijn het beschermen van natuurlijk verjongde bomen (tending), door het verminderen van concurrentie met lianen en commercieel minder waardevolle bomen, en door de aanplant van commerciële soorten in openingen veroorzaakt door RIL (onderplanting ter verrijking van het resterende bos). Deze behandelingen vereisen echter financiële investeringen, die de winstgevendheid kunnen verminderen. Aan de andere kant, kunnen deze behandelingen ook een meerwaarde vormen, waardoor beheerd bos beter kan concurreren met andere vormen van landgebruik. In dit proefschrift komen de volgende vragen aan bod: 1) Hoe reageert de verjonging van commerciële boomsoorten op de verschillen in verstoringintensiteit als gevolg van exploitatie? 2) Hoe reageert de verjonging van commerciële boomsoorten op de middellange termijn op verstoringen veroorzaakt door exploitatie volgens RIL? 3) Welke van de twee bosbouwkundige ingrepen na de oogst, in de open plekken, zijn het meest geschikt: het beschermen van de natuurlijke verjonging, of extra aanplant gevolgd door bescherming? 4) In hoeverre zijn de bosbouwkundige ingrepen na de oogst zoals de bescherming van de natuurlijke verjonging en de extra aanplant, winstgevend op lange termijn?

De korte-termijn effecten van RIL op de verjonging van zeven commerciële boomsoorten werd onderzocht in Hoofdstuk 2, door middel van een experiment uitgevoerd in

een intensief bestudeerd proefvlak in het 600.000 ha groot Tapajós National Forest, in het Oost-Amazonegebied in Brazilië. De onderzochte soorten behoren tot drie functionele groepen: de langlevende pioniers (LLP) *Bagassa guianensis* en *Jacaranda copaia*, de gedeeltelijk schaduw-tolerante (GST) *Hymenaea courbaril*, *Dipteryx odorata*, en *Carapa guianensis*, en de volledig schaduw-tolerante (TST) *Symphonia globulifera* en *Manilkara huberi*. Alle individuen van deze soorten kleiner dan 20 cm in diameter werden geïnventariseerd en drie keer gemeten vóór de kap (in de periode 2002-2003) en vervolgens twee keer erna (in 2003 en 2004). In het gekapte gebied werden 28 transecten bemonsterd bestaande uit proefvlakken van 10 x 10 m, die in totaal 24,39 ha omvatten. De gemiddelde intensiteit van de oogst was 22 m³ hout per ha (21% van het oorspronkelijke commerciële volume).

In Hoofdstuk 3 worden de middellange termijn effecten van RIL geëvalueerd, waartoe een deel van de gekapte transecten twee keer extra gemeten werden (in 2006 en 2009), en vergeleken met drie transecten in een ongekapt bos opgemeten in 2006 en 2009 (totaal opgemeten gebied: 2,37 ha).

Hoofdstuk 4 beschrijft het onderzoek uitgevoerd in het gebied van het Orsa Florestal, een bosbouwbedrijf in de Jari-vallei, in het Oost-Amazonegebied. Hier werden 64 2-jarige kap openingen met een gemiddelde grootte van 427,2 m² bemonsterd. In 34 van deze openingen is extra aanplant toegepast; daarvan werd in 15 openingen de jonge aanplant beschermd, met de overige 15 als controle. Groei en mortaliteit van de individuele bomen werden gedurende vier jaar gemeten. In hoofdstuk 5 worden de effecten van bescherming en extra aanplant op houtproductie en op de winstgevendheid op de lange termijn (60 en 90 jaar) geëvalueerd. De twee bosbouwkundige behandelingen werden vergeleken met een controle behandeling volgens de huidige standaardprocedures van RIL (zonder behandeling na de oogst), uitgaande van verschillende lange-termijn rentetarieven, stijgende prijzen voor rond- en gezaagd hout, en toenemende oogstkosten.

De resultaten tonen aan dat RIL geen destructief effect had op het geoogste bos: 52,5% van het oppervlakte bleef relatief onaangetast en slechts 9,2% was sterk verstoord door houtkap. Alle soorten met uitzondering *C. guianensis* stegen in dichtheid na kap. De LLP soorten namen vooral in dichtheid toe in sterk verstoorde percelen, terwijl GST en TST soorten in dichtheid toenamen in percelen met lage verstoring niveaus. Het positieve effect van de verhoogde dichtheden van de gekapte soorten was kortstondig en verdween na twee jaar, echter de gewijzigde bosstructuur was nog steeds waarneembaar na 6 jaar. RIL had een

positief effect op de hoogtegroeï van *S. globulifera* en op de diametergroeï van *C. guianensis*. Planten in verstoorde percelen hadden een snellere hoogtegroeï dan planten in de ongestoorde percelen, maar hetzelfde patroon werd niet waargenomen voor diametergroeï.

Van de 10 geanalyseerde soorten, reageerden vijf (de LLP *Goupia glabra* en *Laetia procera*, en de GST *Dinizia excelsa*, *Tachigali myrmecophila* en *Trattinnickia* sp.) positief op bosbouwkundige ingrepen. Op basis van deze resultaten, wordt bescherming van verjonging aanbevolen voor geëxploiteerde gebieden tropisch bos met voldoende natuurlijke verjonging van commerciële soorten. Extra aanplant zou alleen moeten worden toegepast voor soorten met een hoge initiële groei en met hoge commerciële waarde. Zowel bescherming van verjonging als extra aanplant was niet winstgevend onder lange termijn rentes van 3%, 6% en 9%. Alleen gezaagd hout geproduceerd onder de behandeling, met een prijsstijging van 750% in 60 jaar, zou de behandeling winstgevend kunnen maken. Vermindering van de kosten en verbetering van de bescherming en extra aanplanttechnieken zouden desalniettemin deze bosbouwkundige ingrepen na oogst winstgevend kunnen maken voor zowel rondhout als gezaagd hout. Zodra deze ingrepen meer renderend worden, kan beheerd bos een concurrerend landgebruik worden in de Amazone.

Sumário

A Amazônia abrange aproximadamente 60% de todas as florestas tropicais úmidas remanescentes no mundo e a maior parte de sua área fica em território brasileiro, onde quase 20% da cobertura florestal foi perdida devido ao desmatamento. O manejo florestal na Amazônia brasileira começou experimentalmente na década de 1970, quando o Sistema Uniforme Malaio foi adaptado às condições locais em um sistema silvicultural policíclico e, posteriormente, acrescido de elementos do sistema CELOS. As técnicas de colheita também foram melhoradas com a introdução de técnicas de exploração de impacto reduzido (EIR). A EIR tem menos efeitos negativos ao ambiente do que exploração madeireira convencional, tendo impacto menor ou nulo sobre a fauna e flora e sobre as populações das espécies exploradas. Alguns estudos, porém, mostram que florestas manejadas sob as práticas atuais de EIR podem não ter regeneração suficiente de espécies comerciais e que as espécies exploradas terão produção madeireira mais baixas em futuros ciclos de corte. Entre as opções possíveis para mitigar esses problemas está a aplicação de tratamentos silviculturais pós-colheita. Alguns candidatos promissores são a condução da regeneração natural estabelecida para diminuir a concorrência com cipós e outras espécies de menor valor comercial, e o enriquecimento de clareiras criadas pela EIR. Estes tratamentos, no entanto, exigem investimentos financeiros de longo prazo, o que pode reduzir a sua rentabilidade. Por outro lado, eles também podem agregar valor às florestas, permitindo assim que a floresta manejada possa competir melhor com outros usos da terra, que têm um impacto mais negativo sobre a cobertura florestal.

Nesta tese as seguintes questões foram abordadas: 1) Como a regeneração de espécies arbóreas comerciais respondem aos diferentes níveis de distúrbios criados pela EIR? 2) Como a regeneração de espécies de árvores comerciais respondem a médio prazo a perturbações causadas pela EIR? 3) Qual dos dois tratamentos silviculturais pós-colheita é o mais adequado: tratamentos silviculturais para conduzir a regeneração natural ou enriquecimento de clareiras seguido por tratamentos silviculturais? 4) Até que ponto é rentável a aplicação dos tratamentos pós-colheita de condução da regeneração natural ou enriquecimento em clareiras no longo prazo?

O efeito de curto prazo da EIR na regeneração de sete espécies de árvores comerciais foi avaliada no Capítulo 2, por meio de um experimento realizado em uma parcela de estudo

intensivo na Floresta Nacional do Tapajós (600.000 ha), Amazônia Oriental, Brasil. As espécies estudadas pertencem a três grupos funcionais: as pioneiras de vida longa (PVL) *Bagassa guianensis* e *Jacaranda copaia*; as parcialmente tolerantes à sombra (PTS) *Hymenaea courbaril*, *Dipteryx odorata*, e *Carapa guianensis*, e as totalmente tolerantes à sombra (TTS) *Symphonia globulifera* e *Manilkara huberi*. Todos os indivíduos dessas espécies < 20 cm em diâmetro foram inventariados e medidos três vezes (em 2002-2003) antes e duas vezes depois da colheita (em 2003-2004). A área explorada foi amostrada em 28 transectos em parcelas de 10 x 10 m, cobrindo um total de 24,39 ha. A intensidade média da colheita foi de 22 m³ ha⁻¹ (21% do volume original comercial). No capítulo 3 é avaliado os efeitos a médio prazo da EIR, parte desses transectos explorados foram medidos mais duas vezes (em 2006 e 2009) e comparados com outros três transectos estabelecidos em uma floresta não explorada adjacente e também medidas em 2006 e 2009 (total da área medida igual a 2,37 ha).

O Capítulo 4 descreve a pesquisa realizada na área de manejo florestal da empresa Orsa Florestal S/A no Vale do Jari, Amazônia Oriental, Brasil. Aqui, 64 clareiras de dois anos de idade com tamanho médio de 427,2 m² foram amostradas. Em 34 dessas clareiras o tratamento de enriquecimento de clareiras foi aplicado, 15 foram submetidos a tratamentos silviculturais sobre a regeneração natural e os 15 restantes foram usados como controle. As taxas de mortalidade e crescimento dos indivíduos monitorados foram medidos por quatro anos. No capítulo 5, as respostas dos indivíduos foram extrapoladas no longo prazo (60 a 90 anos) para avaliar a produção de madeira e rentabilidade. Os dois tratamentos silviculturais foram comparados a um tratamento controle representando os atuais procedimentos na EIR (quando as clareiras não recebem tratamentos de pós-colheita), assumindo diferentes taxas de juro de longo prazo, aumento dos preços para todo e madeira em tora e serrada, e aumentando nos custos de colheita.

Os resultados mostram que a EIR não tem um efeito destrutivo sobre a floresta explorada, 52,5% da área permaneceu intacta e apenas 9,2% ficou bastante perturbada pelas atividades de exploração. Todas as espécies exceto *C. guianensis* aumentaram em densidade após a exploração. As espécies PVL tiveram o maior aumento em densidade nas parcelas altamente perturbadas, enquanto as PTS e as TTS aumentaram em densidade nas parcelas com níveis de perturbação mais baixas. O efeito positivo do aumento da densidade das espécies exploradas foi efêmero e desapareceram dois anos após a exploração, mas a estrutura da floresta modificada ainda era perceptível após 6 anos. A EIR teve um efeito positivo na taxa de crescimento em altura de *S. globulifera* e em diâmetro para *C. guianensis*. As plantas

que estavam nas parcelas sob grande perturbação tiveram taxas mais rápidas de crescimento em altura do que as plantas em não perturbadas, mas o mesmo não foi observado para as taxas de crescimento em diâmetro.

Das 10 espécies analisadas, cinco (as PVL *Goupia glabra* e *Laetia procera*, e a TTS *Dinizia excelsa*, *Tachigali myrmecophila*, e *Trattinnickia* sp.) responderam positivamente aos tratamentos silviculturais. Com base nesses resultados, o tratamento silvicultural sobre a regeneração natural é recomendado para áreas de floresta tropical explorada com regeneração natural de espécies comerciais suficiente. O enriquecimento em clareiras deve ser aplicado utilizando apenas espécies com altas taxas de crescimento inicial e valor comercial. Tanto tratamentos silviculturais na regeneração quanto enriquecimento em clareiras não foram rentáveis sob as taxas de juro de longo prazo de 3%, 6% e 9% e apenas madeira serrada produzida através aplicação de tratamentos silviculturais na regeneração sob um aumento de 750% em 60 anos no preço da madeira faria o tratamento ficar rentável. A redução de custos e melhorias no nas técnicas de tratamento silviculturais na regeneração e no enriquecimento de clareiras faria, entretanto, estes tratamentos pós-colheita serem rentáveis, tanto para madeira em tora como serrada. Uma vez sendo estes tratamentos mais rentáveis, as florestas manejadas seriam um uso da terra economicamente mais competitivo na Amazônia.

Acknowledgements

My thesis was possible due to the cooperation between the Brazilian Agricultural Research Corporation (EMBRAPA) and Wageningen University and Research Centre (WUR) through the Competing Claims on Natural Resources Programme, and the IPOP Scaling and Governance programme. Fieldwork was possible thanks to the cooperation of the administration of the Tapajós National Forest (Brazilian Ministry of the Environment), the forestry companies Orsa Florestal S/A, Maflops, and Cikel Brasil Verde, and the Ambé project.

I would like to thank my supervisor Prof. Frits Mohren and my co-supervisor Prof. Bas Arts for the support provided during the whole PhD course. I am very grateful to my daily supervisor Dr. Marielos Peña-Claros for discussions and constant help and patience to improve manuscripts and my local supervisor and coordinator of the Gap Management project José do Carmo Lopes for discussions and suggestions ever since the early stages of this research. I acknowledge my academic advisor in Embrapa and coordinator of the Dendrogene project, Dr. Milton Kanashiro for his constant support beginning one year before starting my PhD, Dr. Oriel de Lemos for his encouragement to start a PhD, Dr. Claudius van de Vijver, coordinator of the PhD Education Program of the PE&RC, and Maja Slingerland, coordinator of the Competing Claims on Natural Resources programme. I also acknowledge Fábio Diniz and Peter Groenendijk, the paranymphs in my PhD defense.

I am indebted to, Socorro Ferreira, Ademir Ruschel, Syglea Lopes, Ian Thompson, Patrick Jansen, Bryan Finegan, Donald Franklin, Christopher Baraloto, Lucas Mazzei, Marjanke Hoogstra, Silvine Rodrigues, Ricardo Kilca, Reitze de Graaf, and the anonymous reviewers of the articles published or in review for their encouragement, discussions, comments, and suggestions that really improved the quality of my thesis.

I am grateful to my English teachers in Brazil, Edmundo Xavier and Mary Hawkins for their patience and encouragement that helped me to overcome hurdles and believe in my potential. I thank Dr. Joy Burrough for the language editing of the summary and chapters 1 and 6. I also thank Peter Groenendijk, Peter Schippers, and Frits Mohren for the translation and review of the summary in Dutch and José do Carmo Lopes for the review of the summary in Portuguese.

Acknowledgements

A pleasant and productive working environment in the Forest Ecology and Forest Management (FEM) Group was possible not only due to WUR facilities but because of the nice times I shared with people. I am grateful to the staff members of FEM: Frits Mohren, Joke Jansen, Frans Bongers, Britta Eilmann, Leo Goudzwaard, Jan den Ouden, Marielos Peña-Claros, Lourens Poorter, Ute Sass-Klaassen, Peter Schippers, Frank Sterck, Ellen Wilderink, Patrick Jansen, Pieter Zuidema, and Hans Polman and the invited researchers Stefan Schnitzer, Esron Munyanziza, Gjin Ceca, Cesar Perez-Cruzado, and Bryan Finegan for the exchange of ideas. Many thanks my PhD colleagues Abeje Eshete, Lucy Amissah, Geovana Carreño Rocabado, Paul Copini, Motuma Tolera, Peter Groenendijk, Ana Catarina Jakovac, Arnold van Gelder, Samadori Honoré Biao, Madelon Lohbeck, Corneille Ewango, Gabriel Muturi, Jean Ndyambaje, Kwame Oduro, Estela Quintero Vallejo, Tefera Mengistu, Lars Markesteijn, Marlene Soriano, Marisol Toledo, Masha van der Sande, Mart Vlam, Meenakshi Kaul, Peter van der Sleen, Monique Weemstra, Erich Grothe, Emiru Hizikias, Yosias Gandhi, and Mathieu Decuyper for talks, help, discussions, and nice times when we all faced the same challenges.

The success of this thesis is also due to the logistic support and complementary data provided by the forestry companies, research institutions, and projects, especially by Antonio Abelardo Leite, Kátia Regina Silva, Domingos Sanchez, Felipe Faria, Perez Correa, Orlando dos Santos Watrin, Antonio Guilherme Campos, Raimundo Cosme de Oliveira Jr., Janitoni Lima da Silva, Valdemir Rodrigues de Lira, Nilson de Souza Carvalho, Jose Augusto Silva, Roberto dos Santos, Jean Freitas dos Santos, Philippe Sablayrolles, Evandro Ferreira, Francys Nava, and Wandreia Baitz.

The MSc students Vanessa Falkowski and Anna Liza Bais, for whom I was one of the supervisors, made an important contribution to developing different parts of my thesis. I acknowledge their very good work.

I thank my colleagues from Embrapa, who are also taking part in the Competing Claims Brazil, André Novo, Daniel Kimpara, Fábio Diniz, and Murilo Arruda for friendship and mutual constant support in all phases of the PhD, since the first bureaucratic steps before starting the PhD to the post-defense re-adaptation in Brazil. I am grateful to them for helping me to face and overcome the seemingly endless number of challenges posed by taking a PhD under strict time constraints and having to cope with the high quality standards required by the two institutions with different profiles which we worked for.

I acknowledge José do Carmo Lopes for friendship and eight years of cooperation, from which I learned a lot about forest science. The fundamental ideas tested in this thesis are a result of this fruitful partnership.

The years spent in the Netherlands were very good and an unforgettable experience. So, I must thank the Dutch people and all my Dutch friends who warmly accepted me in their wonderful country even though I do not speak their language.

My gratitude to my family who provided me essential support in the first months of 2011 during my “homeless” period, when I was based in Santa Maria, south Brazil. To my brother Frederico Schwartz and my sister-in-law, Daroonwan Schwartz who, though living in Germany, helped me in The Netherlands. To my mother-in-law Marileusa Ferreira Teichmann, who was a great help during her two-month visit to The Netherlands, coincidentally the last two months of writing my thesis.

My acknowledgement and apologies to the people and institutions that I may have forgotten to mention but who, in one way or another, contributed to the success of my research.

Finally I must say I am really indebted to my wife Simone Ferreira Teichmann for her great incentive, patience, and essential support during all phases of my PhD. The long periods of being far from each other and the countless farewells in airports in Brazil (Porto Alegre and Belém) or in the Netherlands (Schiphol) were not easy, especially when I was incommunicado in the Amazon forest. I apologize to her for the occasions I did not correspond to what she expected.

Acknowledgements

Short biography

Gustavo Schwartz was born on 1st August 1974 in Santa Maria, Rio Grande do Sul state, Brazil. He is the son of Cezar Augusto Schwartz and Maria Elizabeth Schwartz, and is married to Simone Ferreira Teichmann. In 1992 he obtained his high school diploma in Agriculture and Livestock, finishing his high school level in the Agricultural School of Santa Maria (CASM). In 1999 Gustavo obtained his major in Biological Sciences from the Federal University of Santa Maria (UFSM). Two years later he completed his MSc in Ecology at the State University of Campinas (UNICAMP), in São Paulo state. His master's thesis was on the ecological and evolutionary aspects of predation on larvae of herbivorous insects. From 2001 to 2003 Gustavo was assistant professor in ecology at the University of the Campanha Region (URCAMP), in São Gabriel, Rio Grande do Sul, also teaching biology at the secondary school of the same university in 2003. In August 2003 Gustavo was hired by the the Brazilian Agricultural Research Corporation (EMBRAPA) as a junior researcher in the Forest Management and Conservation Group at the Embrapa Eastern Amazon unit in Belém, Pará state. Since then he has been researching the ecology and management of primary and secondary forests in eastern Amazon.

In 2005, in his capacity as advisor to both the Ministry of Environment and the Ministry of Agriculture, Gustavo participated in a major initiative involving 11 other ministries that resulted in the establishment of seven new nature conservation units. The seven units cover a total of 63,000 km² of primary forest in the eastern Amazon. In 2009 he started his PhD in Wageningen University at the Forest Ecology and Forest Management Group.

After obtaining his doctorate, Gustavo Schwartz intends to return to the Embrapa Eastern Amazon unit, to do research on improving polycyclic silvicultural systems and understanding the ecology of commercial tree species in the Amazon. He also hopes to be able to strengthen collaboration between South American and European research institutions.



Gustavo Schwartz and his wife Simone Ferreira Teichmann.

List of publications

Published / accepted papers

- Schwartz, G., Lopes, J.C.A., Mohren, G.M.J., Peña-Claros, M., 2013. Post-harvesting silvicultural treatments in logging gaps: A comparison between enrichment planting and tending of natural regeneration. (Accepted for publication in *Forest Ecology and Management*).
- Rodrigues, S.T., Schwartz, G., De Almeida, S.S., 2012. Diversidade, síndromes de dispersão e formas de vida vegetal em diferentes estágios sucessionais de florestas secundárias em Tomé-Açu, Pará, Brasil. *Amazônia: Ciência e Desenvolvimento*. *Amazônia: Ciência e Desenvolvimento* 7, 21-31.
- Schwartz, G., Peña-Claros, M., Lopes, J.C.A., Mohren, G.M.J., Kanashiro, M., 2012. Mid-term effects of reduced-impact logging on the regeneration of seven tree commercial species in the Eastern Amazon. *Forest Ecology and Management* 274, 116-125.
- Gonçalves, D.A., Schwartz, G., Pokorny, B., Van Eldik, T., 2010. O uso da classificação de copa de Dawkins como indicador do comportamento ecológico de espécies arbóreas tropicais. *Revista Floresta* 40, 175-182.
- Pinheiro, K.A.O., Schwartz, G., 2009. Aspectos socioeconômicos da comercialização de produtos agrícolas e florestais em sete comunidades rurais no alto Moju, estado do Pará. *Amazônia: Ciência e Desenvolvimento* 5, 41-51.
- Schwartz, G.; Nascimento, N.A., Menezes, A.J.E.A., 2008. Estrutura populacional de espécies de interesse florestal não-madeireiro no sudeste do Pará, Brasil. *Amazônia: Ciência e Desenvolvimento* 4, 117-130.
- Carim, S., Schwartz, G., Da Silva, M.F.F., 2007. Riqueza de espécies, estrutura e composição florística de uma floresta secundária de 40 anos no leste da Amazônia. *Acta Botanica Brasilica* 21, 293-308.

List of publications

- Pinheiro, K.A.O., Carvalho, J.O.P., Quanz, B., Francez, L.M.B., Schwartz, G., 2007. Fitossociologia de uma área de preservação permanente no leste da Amazônia: indicação de espécies para recuperação de áreas alteradas. *Revista Floresta* 37, 175-187.
- Schwartz, G., 2007. Manejo sustentável de florestas secundárias: espécies potenciais no nordeste do Pará, Brasil. *Amazônia: Ciência e Desenvolvimento* 5, 125-136.
- Schwartz, G., Watrin, O.S., Gomes, J.I., 2006. Espécies arbóreas da sede da Embrapa Amazônia Oriental: conservação ex situ e um novo espaço de Educação Ambiental em Belém. *Revista de Ciências Agrárias* 46, 181-194.
- Silva, B.N.R., Watrin, O.S., Sampaio, S.M.N., Schwartz, G., 2005. Zoneamento de áreas potenciais para reflorestamento visando à produção de lenha e carvão como alternativa para os produtores do projeto São Francisco, Sudeste Paraense. *Revista do IESAM* 3, 131-140.
- Di Mare, R. A., Corseuil, E., Schwartz, G., 2004. Morfometria de Papilioninae (Lepidoptera, Papilionidae) ocorrentes em quatro localidades do Rio Grande do Sul, Brasil. I. Comparações com a massa corporal. *Revista Brasileira de Entomologia* 48, 535-545.
- Schwartz, G., Hanazaki, N., Silva, M.B., Izzo, T.J., Bejar, M. P., Mesquita, M., Fernandes, G.W., 2003. Evidence for a stress hypothesis: hemiparasitism effect on the colonization of *Alchornea castaneafolia* A. JUSS. Euphorbiaceae by galling insects. *Acta Amazonica* 33, 275-279.
- Schwartz, G., Di Mare, R. A., 2001. Diversidade de quinze espécies de borboletas (Lepidoptera, Papilionidae) em sete comunidades de Santa Maria, RS. *Ciência Rural* 31, 49-55.

Papers under peer-review

- Schwartz, G, Peña-Claros, M., Lopes, J.C.A., Kanashiro, M., Mohren, G.M.J. Disturbance level and temporal effects of reduced-impact logging on the regeneration of commercial tree species in the Eastern Amazon.

Kilca, R.V., Longhi, S.J., Schwartz, G., Souza, A.M. Fisher discriminant analysis to classify forest communities in the Pampa biome.

Schwartz, G., Bais, A.L.S., Peña-Claros, M., Hoogstra-Klein, M., Mohren, G.M.J., Arts, B.J.M. Profitability of post-harvesting silvicultural treatments applied in logging gaps in the Brazilian Amazon.

List of publications

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)



Review of literature (5.6 ECTS)

- Silvicultural systems applied in tropical forests (2010-2012)

Writing of project proposal (4.5 ECTS)

- Looking at the future: promoting regeneration of commercial species to achieve sustainable harvests in the Brazilian Amazon

Post-graduate courses (4.1 ECTS)

- Linear models; PE&RC (2010)
- Mixed linear models; PE&RC (2010)
- International forestry and global issues; INRA (2010)
- Generalized linear models; PE&RC (2010)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Biotropica: forest ecology (2012)

Deficiency, refresh, brush-up courses (3 ECTS)

- Ecological methods I (2009)
- Ecological methods II (2009)

Competence strengthening / skills courses (0.9 ECTS)

- Interpersonal communication for PhD students; WGS (2009)
- PhD Competence assessment; Lang. Serv. (2009)

PE&RC Annual meetings, seminars and PE&RC weekend (1.2 ECTS)

- PE&RC Day (2011)
- PE&RC Weekend (2011)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)

- Scale and governance meetings and discussions (2009-2010)
- Wageningen evolution and ecology seminars (WEES) (2009-2012)
- Wageningen ecology and forest management chair group scientific presentations (2009-2012)

International symposia, workshops and conferences (5.6 ECTS)

- Annual meeting of the Association of Tropical Biology and Conservation; oral presentation; Arusha, Tanzania (2011)
- IUFRO- Research Priorities in Tropical Silviculture: Towards New Paradigms; oral presentation; Montpellier, France (2011)

Supervision of 2 MSc students; 30 days (6 ECTS)

- Forest ecology and management
- Forest economics

Funding

The fellowship was funded through the Competing Claims Brazil programme between Wageningen University and the Brazilian Agricultural Research Corporation (Embrapa).

The research costs were funded by IPOP Scaling and Governance programme, Wageningen University and Research Centre.

Cover design: Proefschriftmaken.nl || Uitgeverij BOXPress

Printed & Lay Out by: Proefschriftmaken.nl || Uitgeverij BOXPress

Published by: Uitgeverij BOXPress, 's-Hertogenbosch – The Netherlands

Cover photo: Forest management area of Orsa Florestal – Brazil by Gustavo Schwartz